

Department of
Mining and Metallurgical Engineering

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Halifax, Nova Scotia

**Transmission Electron Microscopy Study
on the Effects of Simulated Rail Loading
on an Experimental Premium Rail Steel**

FINAL REPORT

by

E.E. Laufer and C. MacDonald

Technical University of Nova Scotia

Work on this project was conducted under the auspices of the Canada
Centre for Mineral and Energy Technology
Energy, Mines and Resources Canada

DSS File Number: 20SU.23440-0-9191

DSS Contract Serial Number: OSU81-00231

CANMET Project Number:

May, 1985

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1. SUMMARY

Sections of Nippon head-hardened rail and standard rail were examined. Both rails had seen essentially the same service at F.A.S.T., i.e., about 250 MGT of mixed dry and lubricated wear in a 350 m radius (50°) curve. On visual inspection, the standard rail was seen to have lost much more material at the gauge face than the head-hardened rail. On the other hand, the head-hardened rail showed numerous sub-surface cracks or spalled regions. Spalls were of the order of 6 mm long and 1.5 mm deep, and were not observed in the standard rail.

The microhardness of the standard rail rose from about 300 HK at a depth of about 1 mm to over 700 HK at the gauge corner and gauge face surfaces, while that of the head-hardened rail rose from about 430 HK at a depth of 1 mm to 550 HK - 776 HK at the gauge corner and gauge face surfaces. Thus, the superior wear performance of the head hardened rail cannot be ascribed simply to the development of higher surface hardness.

The initial microstructure of each rail was pearlitic. The standard rail had an initial pearlite spacing of about 285 nm, compared to about 90 nm for the head-hardened rail. After deformation, i.e., near the running surface and especially in the region of the gauge corner, the pearlite spacing in the head-hardened rail had been reduced to about 40-50 nm. In the standard rail, the spacing had been reduced to about 150 nm. In both cases, significant scatter in spacing was observed, indicating inhomogeneous deformation. Further, the standard rail had suffered gross plastic flow or crushing, evidenced by bent pearlite to a depth of at least 1 mm. Near the surface, the cementite lamellae in the standard rail were broken into relatively short lengths. Neither of these phenomena was observed in the head-hardened rail, except to a very limited extent and only very near the surface. We conclude, in agreement

with work cited by Langford⁽¹⁾ that very fine cementite is ductile, while coarser cementite is not capable of significant plastic deformation. Thus, the fine cementite of the head-hardened rail was able to deform to produce a very fine and apparently wear-resistant microstructure at the rail surface. The coarser cementite of the standard rail did not deform to the same degree, but rather fractured. The resulting microstructure was less wear resistant. It is, however, curious that microhardness traverses did not show a corresponding variation in hardness. Rather, both rails hardened to about the same degree, as indicated by Knoop microhardness tests.

The observations are very similar to those made on discs tested on the NRC, 1/10 scale rail wear test rig, and described in our report of December 31, 1983. However, the texture apparently present in the 1/10 scale samples was not observed in the full-scale rails. Further, the spalling observed at the tread surface of the head-hardened rail was not so evident in the 1/10 scale samples. Regarding texture, it must be emphasized that no detailed study of texture was undertaken.

2. INTRODUCTION

Our Contract Report No. OSU81-00231, dated December 31, 1983, described the microstructure observed by TEM in an experimental premium rail steel after simulated rail loading. The steel was tested after heat treatment to pearlite, bainite and tempered martensite, to hardness of 45, 42 and 38 HRC in each case. Among the most striking observations were evidence of significant plastic deformation of the cementite, especially in the pearlite, and of the development of an apparently textured structure with ultra fine grain size. Both of these observations apply particularly to regions very near to the rail surface, where significant work hardening was observed.

Following this work, it appeared useful to examine comparable sections from actual rails. To this end, a length of about 460 mm of each of a head-hardened and a standard rail were obtained from the Facility for Accelerated Service Testing (FAST) of the United States Department of Transport. These rails had each seen about 250 MGT of mixed dry and lubricated service in a 350 m radius (50°) curve at FAST. The objectives of the present work were thus, firstly, to compare the microstructures produced by wear in the two rails and, secondly, to compare the results of full scale tests with those obtained with the 1/10 scale tests. For this second objective, the results obtained with the head-hardened rail may be compared with those obtained with any of the pearlite discs examined earlier. However, no standard rail disc, tested on the 1/10 scale rig, has yet been examined.

3. LABORATORY TECHNIQUES

3.1 TEM Sample Preparation

Standard TEM sample preparation techniques were used. The samples were electroplated with nickel for edge preservation, then sliced on a slow speed diamond saw to about 0.3 mm thickness and hand ground to about 100 μm . 1.5 mm $\varnothing$ discs were cut from the ground slices by EDM, and these were finally thinned in a twin jet device, using a perchloric acid based electrolyte at about -40°C . Difficulty was experienced in the preparation of thin foils from certain samples containing surface or sub-surface cracks. The final polishing in the twin-jet device is terminated when a photo-detector detects perforation of the disc. Such cracks gave false signals and in addition, acted as preferential sites for electropolish attack. Thus, attempts to prepare thin foils from discs cut from samples with surface cracks generally led to discs with large perforations and little or no thin areas. Difficulty was also experienced with separation of the nickel plating from the discs. We believe that in most if not all instances, this was due to the presence of a brittle white-etching layer on the surface of the rails.

Diffraction patterns were taken corresponding to all electron micrographs, and typical patterns are shown in this report. All diffraction patterns shown in this report are from selected areas 3.5 μm in diameter, and are presented at a magnification such that 24 mm corresponds to 5 nm^{-1} . That is, the diameter of the $\{110\}$ ferrite ring is 48 mm.

3.2 Nomenclature

Two rail specimens were examined, head-hardened and standard. These are designated H and S, respectively.

The specimens were samples under the tread, i.e., about halfway across the rail, about one quarter width between the tread and gauge corner, at the gauge corner and at the gauge face. These sample locations, half, quarter, gauge corner and gauge face, are designated H, Q, GC and GF, respectively. Additional indications were used to identify the individual discs examined in the TEM, encoding information about series, number in series and depth below surface. These fine breakdowns were not considered relevant to the present report. Thus, the indication HH means head-hardened, tread (or half) sample, SGC means standard rail, gauge corner, etc.

4. OBSERVATIONS

4.1 Optical Metallography

Optical Metallography was limited to microhardness measurements and the documentation of sub-surface cracks or spalls, especially below the running surface ("H" section) of the head hardened rail. In addition, we were able to document the occurrence of regions of white etching material at the surface of many samples. It is suspected that this is martensite, although a definite identification has not been made. In any case, the material seems brittle and is believed to be the cause of separation of nickel platings from discs being prepared for TEM. In fact, the white etching material failed, and not the nickel-sample interface. Figures 1 and 2 show such white-etching regions.

Figures 3-6 show microhardness curves obtained from unplated samples. Readings closer than 20 μm to the surface, using plated samples, were taken separately for samples HQ, HGC, SQ and SGC. These data are shown in Tables 1, 2 and 3. Microhardness data are discussed in section 5, together with data on pearlite spacings. Figure 7 shows typical spalls or sub-surface cracks at the half or tread section of the running surface of the head-hardened rail. Similar spalls were not seen on the standard rail, nor were they observed on the sections examined of rail discs tested on the NRC rig. Figure 8 shows surface cracks in the head-hardened rail at the quarter section, between the centre of the running surface and the gauge corner. Certain of the discs tested in simulated loading on the NRC rig showed similar cracks, especially the gauge corner of the high rail disc of the hardest pearlite (or transitional pearlite).

4.2 Samples 10 mm Below Rail Surface, TEM

In general, samples taken at this depth were undeformed, and are typical of the original material. The head-hardened and

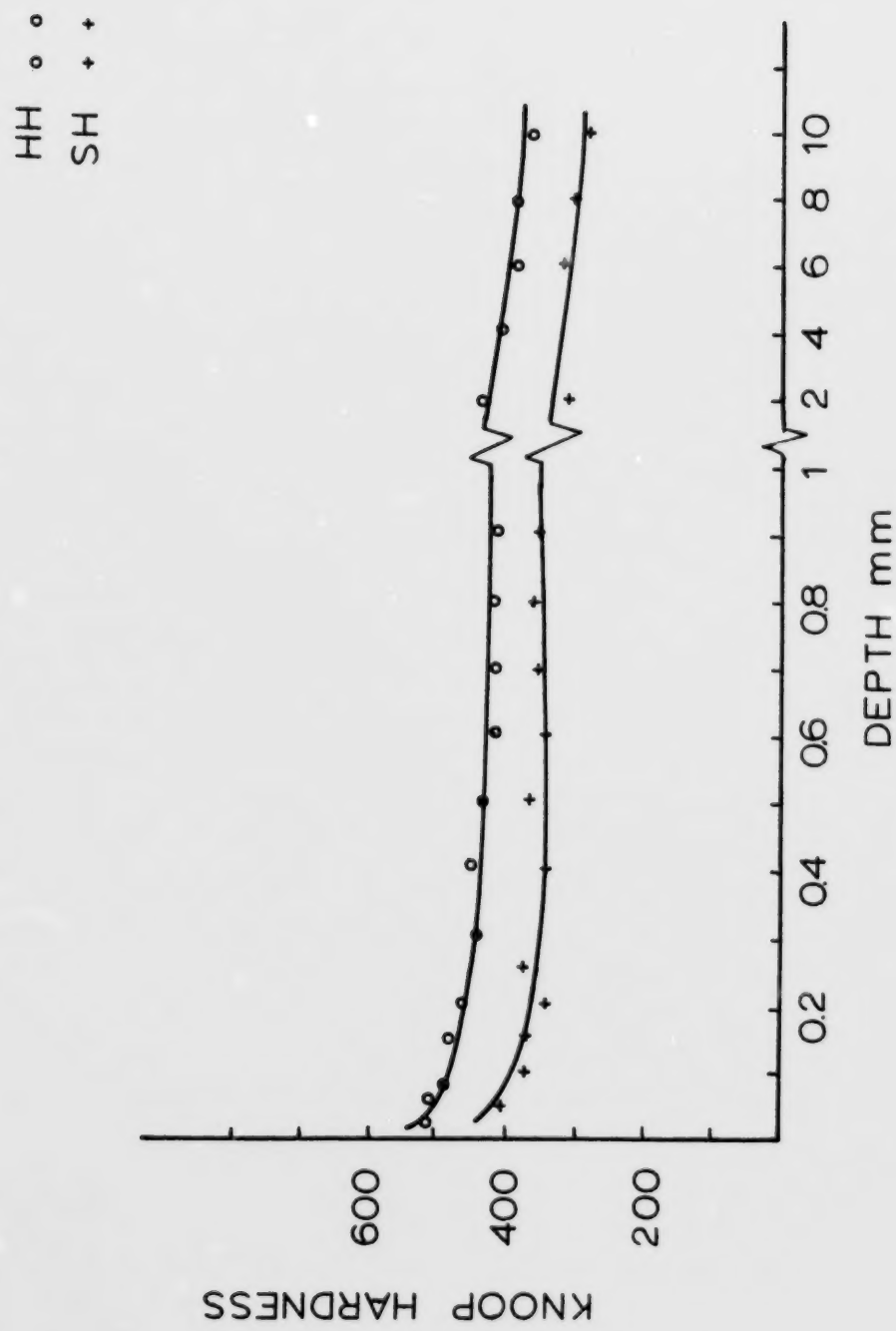


Figure 3. Microhardness vs. depth, half section

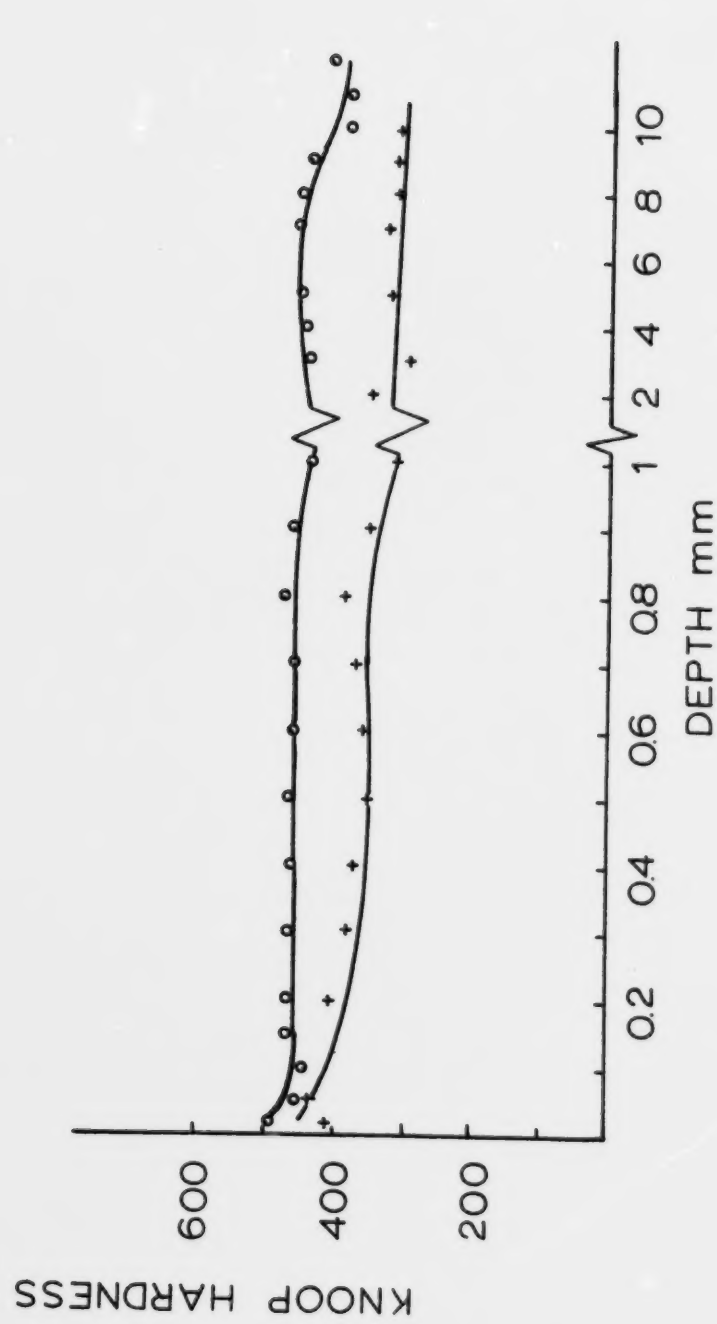


Figure 4. Microhardness vs. depth, quarter section

HGC ○ ○
SGC + +

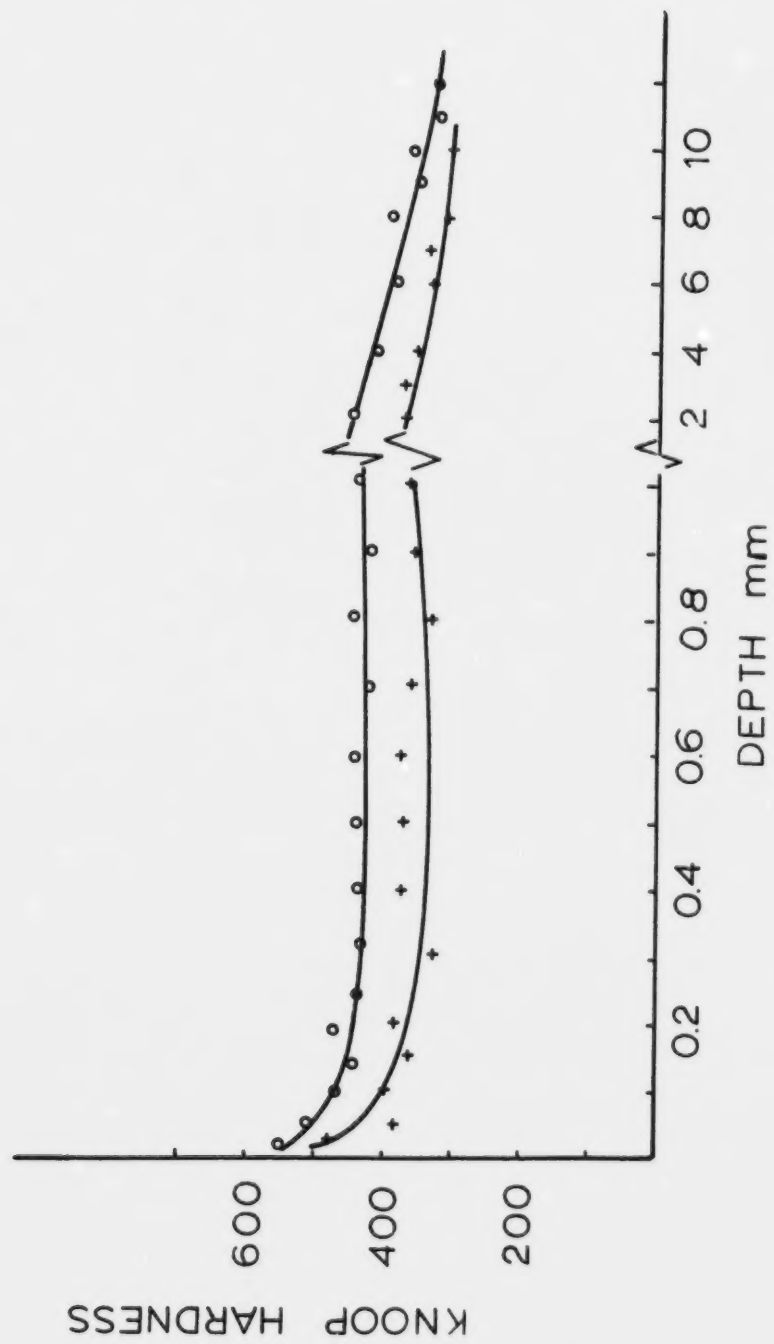


Figure 5. Microhardness vs. depth, gauge corner

HGF ○ ○
SGF + +

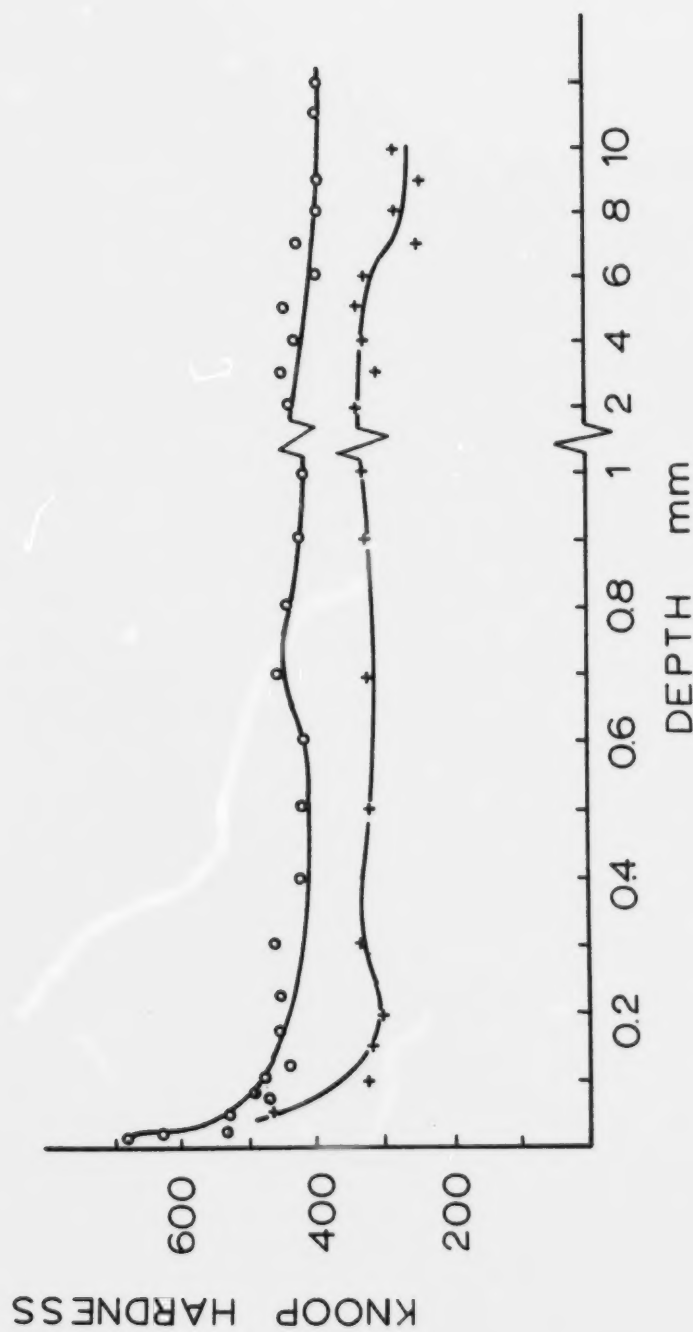


Figure 6. Microhardness vs. depth, gauge face

TABLE 1

Microhardness Traverses, Near Surface

Depth Range, μm

Sample	0	21	41	61	81	101	201	301	401	501	601	701	801	901
	20	40	60	80	100	200	300	400	500	600	700	800	900	1000
HH	530	460	460	440	470	480	440	450	430	410	410	420	410	430
	520		500			460								
SH	460	-	400	-	370	370	360	340	360	340	350	360	350	-
						340								
HQ	470	520	445	-	440	470	470	460	470	460	450	470	460	440
		480	450		430	460								
					445									
SQ	410	-	450	-	-	400	380	370	350	360	370	390	350	305
HGC	500	470	510	440	470	440	440	430	440	440	420	440	420	440
	490		460		430	470		440						
	550													
SGC	-	480	380	-	395	360	330	370	370	370	360	325	350	360
						380						380		
HGF	680	510	500	470	470	440	450	420	420	410	450	440	420	410
	640	530		490		450	460							
	620													
	530													
SGF	-	-	470	-	320	325	340	-	325	-	330	-	330	330
			460		340	360			360					

TABLE 2
Microhardness Traverses, 2-10 mm

Sample	Depth, mm								
	2	3	4	5	6	7	8	9	10
HH	440	430	410	410	380	390	350	380	360
SH	310	350	-	330	320	305	300	270	270 280
HQ	500	440	440	460	410	460	450	440	380
SQ	350	295	-	320	-	330	310	320	305
HGC	440	-	410	-	380	-	390	350	360
SGC	370	370	360 310	-	330 290	340	260 300	325	250 300
HGF	430	440	420	440	390	420	440	380	360
SGF	340	310 280	330	340	330	240	270	240	270

standard rails differed principally in the pearlite spacing, which was about 285 nm in the standard rail, and 90 nm in the head-hardened rail and in their initial hardnesses, which were 23.8 HRC (272 HK) and 37.2 HRC (370 HK), respectively.

4.2.1 Head-Hardened Rail

The head-hardened rail, 10 mm from the wearing surface was substantially undeformed at all locations examined. The individual pearlite colonies or grains had diameters of several micrometers, so that essentially single-crystal diffraction patterns are observed. Occasional sub-boundaries occur, with a corresponding streaking or splitting of spots in the corresponding diffraction pattern. Figure 9 to 12 are typical.

4.2.2 Standard Rail

At 10 mm, the standard rail also is essentially undeformed. The ferrite is generally monocrystalline over the field of any one electron micrograph, so that again, single crystal diffraction patterns are observed. Those few sub-boundaries which are seen are most likely related to the original formation of the pearlite, and not to deformation. Figures 13-18 are typical. Of these, only figure 17a seems atypical, in that broken pearlite is seen. In general, gauge corner deformation was most severe, and this is the only example suggesting deformation at a depth of 10 mm.

4.3 Samples 1 mm below rail surface, TEM.

4.3.1 Head-Hardened Rail

The HH samples, at 1 mm, resemble those at 10 mm. There is very little evidence of deformation, and figures 19 and 20 are typical.

Samples HQ, HGC and HGF also do not seem to be severely deformed. Evidence of deformation consists mainly of two observations. First, there are rather more sub-boundaries present than in the samples HH at 1 mm, or any of the 10 mm samples. This is apparent in figures 21-27 but especially in the streaking or splitting of spots, e.g., {110} in the diffraction patterns. Second, there is a tendency to find dislocations piled up against cementite laths, showing that these laths were acting to re-inforce the ferrite matrix against deformation. This is particularly evident in figures 22 and 24.

4.3.2 Standard Rail

The standard rail samples at 1 mm are strikingly different from the corresponding head-hardened samples, not only for their wider pearlite spacing, but also in that all except the samples SGF show significant deformation of the steel as evidenced by bent cementite lamellae. All samples except SGF also show significant development of sub-boundaries, evidenced by dark-light areas in the micrographs and by streaking or splitting of the spots in the diffraction patterns. For the most part, the sub-grains which have developed are contained within individual ferrite lamellae. Samples of SGC seem most deformed, on the basis of observed microstructure, while SGF are still essentially undeformed, although figure 34a has some suggestion of dislocations piling up against cementite, and one or perhaps two broken cementite lamellae are visible in figure 35 (centre). Figures 28-35 show typical microstructures in the standard rail at 1 mm.

4.4 Samples 250 um below rail surface, TEM

4.4.1 Head-Hardened Rail

At 250 um, the tread samples (HH) still show very little evidence of deformation, and figures 36 and 37 are quite comparable to figures 19 and 20. However, samples HQ and HGC show deformation at 250 um. While very little deformation is evident in figure 38, figure 39a shows bending of the pearlite, somewhat similar to that seen in the standard rail at 1 mm. However, such bent pearlite was relatively rare at any location in the head-hardened rail. On the other hand, the increased polygonization seen in the diffraction pattern, figure 39b, is typical of more severely deformed regions.

Figure 40 shows the HGC region at 250 um. Here, deformation is evident in the significant development of sub-grains (figure 40a) and in the somewhat increased dislocation density seen in figure 40c. Again, figure 40c shows dislocations piled against the cementite laths, indicating re-inforcement of the ferrite matrix by the cementite.

In the HGF regions, damage is also relatively minor. Figure 41 shows gently curved pearlite, and figure 42, the moderately high dislocation density.

4.4.2 Standard Rail

At 250 um and closer to the surface, the worn standard rail is most strikingly characterised by broken pearlite lamellae and by bent lamellae. While these features are occasionally seen on the head-hardened rail, they are rare. Thus, figure 43a shows fractured cementite lamellae, and figure 44 shows bent lamellae in sample SH. Figures 43a and b also show that a certain degree of polygonization has taken place, with new sub-grains and grains of varying lengths having formed, generally

within individual pearlite lamellae. Figures 45 to 47 tell a similar story for sections SQ, as do figures 48 to 50 at the SGC section. At the gauge face, in contrast, the deformation seems less severe, and figure 51 again shows almost undeformed pearlite.

4.5 Samples 50 um below rail surface, TEM

Certain observations are common to both the head-hardened and standard rails at 50 um. Bent pearlite lamellae are seen in both cases, which were not seen in samples tested on the 1/10 scale rig, described in our earlier report (2). These bent lamellae were generally found in quite distinct deformation bands, approximately parallel to the wearing surface of the rail, and this was particularly evident in the head-hardened rail. Generally, both pearlite lamellae and the observed deformation bands were parallel to the wearing surface, although this was less true for the GF samples. Severe break-up of the cementite plates was observed only in the standard rail samples. Significant grain refinement or polygonization was observed in both S and H samples, and this is best seen in the diffraction patterns.

All micrographs, from figure 52 on, are marked to indicate the approximate trace of the wearing surface of the rail, for comparison with pearlite and deformation band directions. Generally, this direction runs approximately 120° - 300° , considering the base of the micrograph (left - right) to run 180° - 0° .

4.5.1 Head-Hardened Rail

At 50 um below the running surface, the head-hardened rail shows a few broken lamellae (figure 52) and bent pearlite (figure 53). However, broken cementite lamellae are still

relatively rare. Sections HQ and HGC show more deformation than do HH. Thus, figure 54 shows pearlite spacing as fine as about 28 nm, and figure 55 shows a distinct deformation band of bent pearlite. In spite of this severe deformation, large accumulations of dislocations do not generally occur, and figure 56 is typical. Figure 57 is typical of section HGC. Dislocation density is relatively low, broken lamellae are not seen in this micrograph, but the pearlite is essentially all parallel to the wearing surface of the rail. Again, at 50 um, the GF sections show less deformation: the pearlite is not clearly parallel to the wearing surface, the spacing is not so fine and broken or bent lamellae are absent.

4.5.2 Standard Rail

The most characteristic feature of the standard rail, at 50 um, is the great number of broken cementite plates. These have broken or in some cases apparently moved with respect to the matrix in such a way as to leave voids, which the TEM reveals as bright clear areas (Figures 59,60). These breaks are somewhat less frequent in the SQ samples than in the SH. SGC is quite similar to SQ. In all of these, SH, SQ and SGC, the pearlite lamellae, and, when they occur, the bent pearlite deformation bands, are essentially parallel to the wearing surface. SGF, on the other hand, again shows very little deformation (figure 65).

4.6 Samples 0-30 um below rail surface, TEM

Great difficulty was experienced in obtaining samples in this depth range, due to surface cracks, and occasional separation of plating and sample, as described in sections 3.1 and 4.1 above. The worst was the HGC series, where we were unable to obtain a sample in the 0-30 um range.

Generally, samples in this range resembled those at 50 μm .

4.6.1 Head-Hardened Rail

The central or H section of this rail shows relatively little obvious evidence of damage, and is quite similar to that at 50 μm . Figures 66 and 67, each at about 24 μm , are typical. On measuring, one finds pearlite spacings in the 40-80 nm range, as at 50 μm , compared to an average spacing of about 90 nm in the new material. Also, the diffraction patterns, especially figure 67b, show polygonization.

Moving to the HQ section, damage is more apparent. Figure 68, at 20 μm , shows bent pearlite, with the deformation band generally aligned with the trace of the wearing surface. One or two broken cementite lamellae are seen, and a moderate dislocation density. Figure 69, at 25 μm , shows pearlite aligned with the wearing surface. The diffraction patterns in both cases show polygonization.

Finally, figures 70-72 show the microstructure at the gauge face, HGF. Figure 70 at 8 μm shows pearlite which is less well aligned than that seen in other sections, and with a rather higher dislocation density. Figure 71, at 20 μm , is much more like the 50 μm samples. The diffraction pattern (figure 70b) shows that a fine-grained microstructure has developed, and this is seen more explicitly in the dark-field micrograph, figure 72.

4.6.2 Standard Rail

Again, the near-surface samples are very similar to the 50 μm samples. Figure 73 shows aligned pearlite, broken lamellae and polygonization at 20 μm in the SH section. Figure 74a at 30 μm

is similar to 73a, while figure 74b, a dark field micrograph using a segment of the $\{110\}$ ring, shows graphically the fine grain size which has developed.

Figures 75 and 76 show the SQ section at 10 μm and 15 μm , respectively. Figure 77 shows SGC at 30 μm .

Figure 78 shows SGF at 15 μm , and even at this depth, very little damage is observed. In contrast, another area is shown, at 20 μm , in figure 79. Here, a very fine, aligned structure has developed. The reason for this discrepancy is not clear.

TABLE 3
Microhardness readings, HK, plated samples

Depth, um	SAMPLE			
	HQ	HGC	SQ	SGC
4	510 476 476	662 734	-	719 743
5	-	719 713 676 776	-	670 710
6	-	-	-	734
7	-	662	490 500	584
8	460	-	485	-
9	-	600	-	563
10	-	607 783	484	690 631
12	-	662	-	-
13	-	720	-	-
15	-	601	-	-
18	-	-	-	543 524 793
25	-	563	-	-
30	-	-	454	499
35	-	497	-	563
50	424 431	492 475	410 -	424 414
55	-	450 472	400	-
60	-	-	-	431
66	-	-	-	389
100	-	407	-	377 -

5. DISCUSSIONS

The present study raises more questions than it answers. In this section, we consider some of these questions.

Most of the information gathered is qualitative, however, some of the micrographs permit measurements of cementite spacing or, rather, repeat distance. Such data are shown in Table 4, together with a standard deviation where appropriate, and in Figures 80 and 81, for samples HGC, HQ, SGC and SQ. It is interesting to note that the data for samples HGC and HQ are not significantly different, and indeed, all points can be fitted to a line:

$$d = 7.0 \ln x + 26.5 \quad (5.1)$$

with a correlation coefficient $r = 0.97$. Here, d is cementite spacing in nm, and x is depth below wearing surface, in μm .

Table 4

Cementite spacings vs. depth, selected samples

Depth, μm	Spacing, nm (Standard deviation in parentheses)							
	HGC		HQ		SGC		SQ	
10^4	90		90		285		285	
10^3	71	(9)	80	(16)	180		273	
250	69	(1)	63	(15)	154	(19)	243	(23)
50	59		51	(22)	111	(46)	117	(5)
<25	-		44	(5)	120	(57)	149	(31)

On the other hand, data for the samples SGC and SQ are quite different. The four data points nearest the wearing surface of sample SGC are fitted by a line:

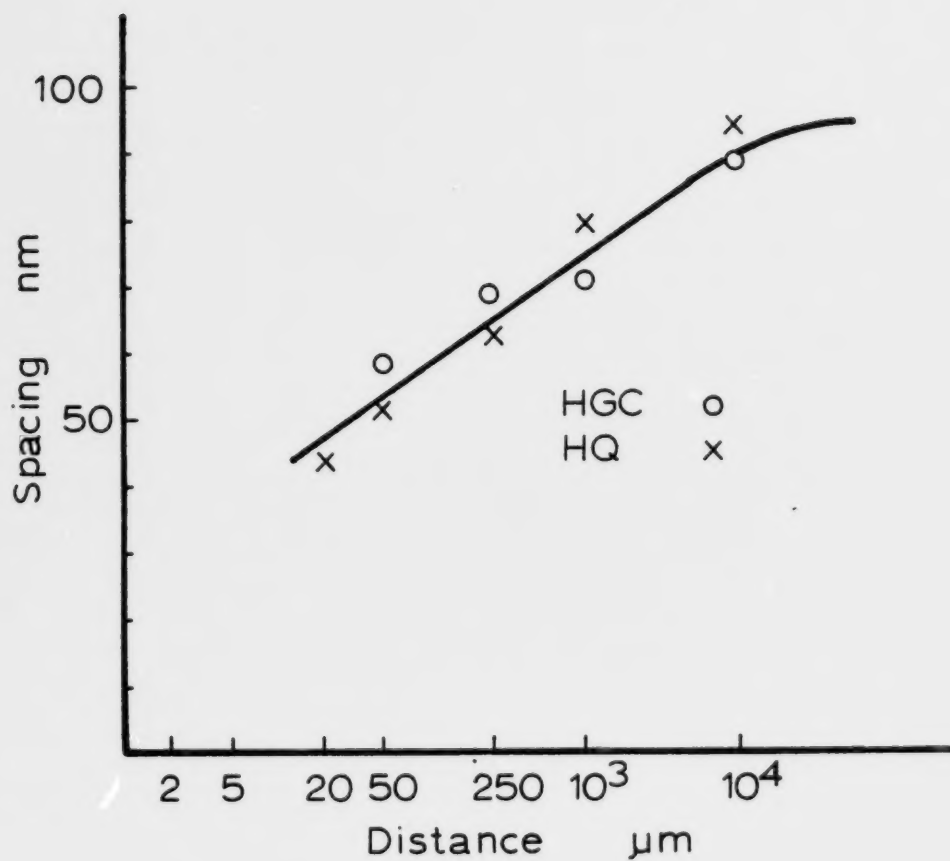


Figure 30. Cementite spacing vs. distance, head hardened rail.

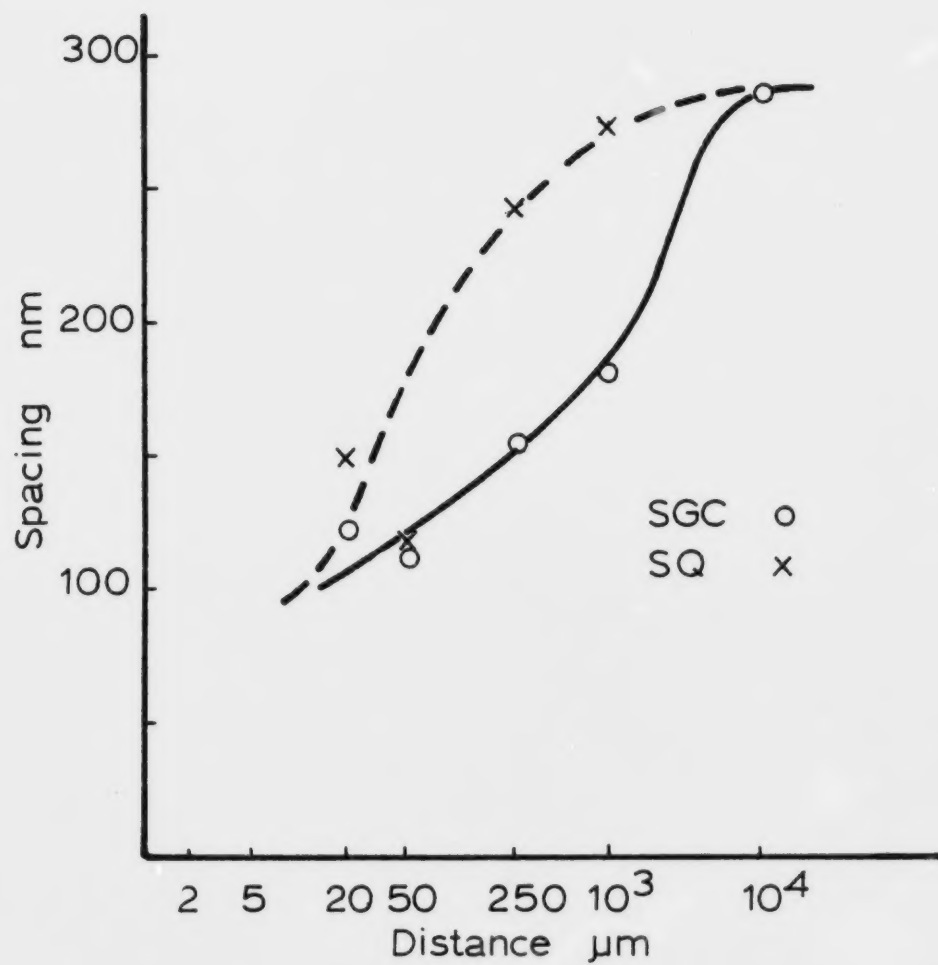


Figure 81. Cementite spacing vs. distance, standard rail.

$$d = 17 \ln x + 57 \quad (5.2)$$

with a correlation coefficient $r = 0.9$.

The maximum deformation, and maximum microhardness were observed on gauge corner samples. Table 5 correlates average microhardnesses using data from Tables 1 and 3, with observed cementite spacing, estimated from Figures 80 and 81, making use of the linear relations given above. From these data, we may plot microhardness as a function of distance below the wearing surface, Figure 82. From this figure it is apparent that there is no sensible difference in surface hardness between the two samples. The difference in microhardness only becomes noticeable below about 50 μm . The data from Figures 80-82, as summarized in Table 5, may also be manipulated to correlate microhardness and cementite spacing. Generally, we observe that the finer the spacing, the harder the metal. However, when we ask for more detail, the story is less satisfying. The data may be fitted to a Hall-Petch type of equation. For this purpose, we observe that either yield or ultimate stress are linearly related to hardness (4). Then the Hall-Petch relation may be written.

$$(\text{HK}) = a + kd^{-1/2} \quad (5.3)$$

However, the data fit equally well to an equation of the form

$$(\text{HK}) = a + kd^{-1} \quad (5.4)$$

or to a quadratic as proposed by Langford (1). For samples HGC we obtain:

$$\text{HK} = 8.41 \times 10^3 d^{-1/2} - 671, \quad r = 0.95 \quad (5.5)$$

$$\text{or, HK} = 2.83 \times 10^4 d^{-1} - 49.4, \quad r = 0.95 \quad (5.6)$$

$$\text{or, HK} = -1.99 \times 10^3 + 2.62 \times 10^4 d^{-1/2} - 6.02 \times 10^4 d^{-4} \quad (5.7)$$

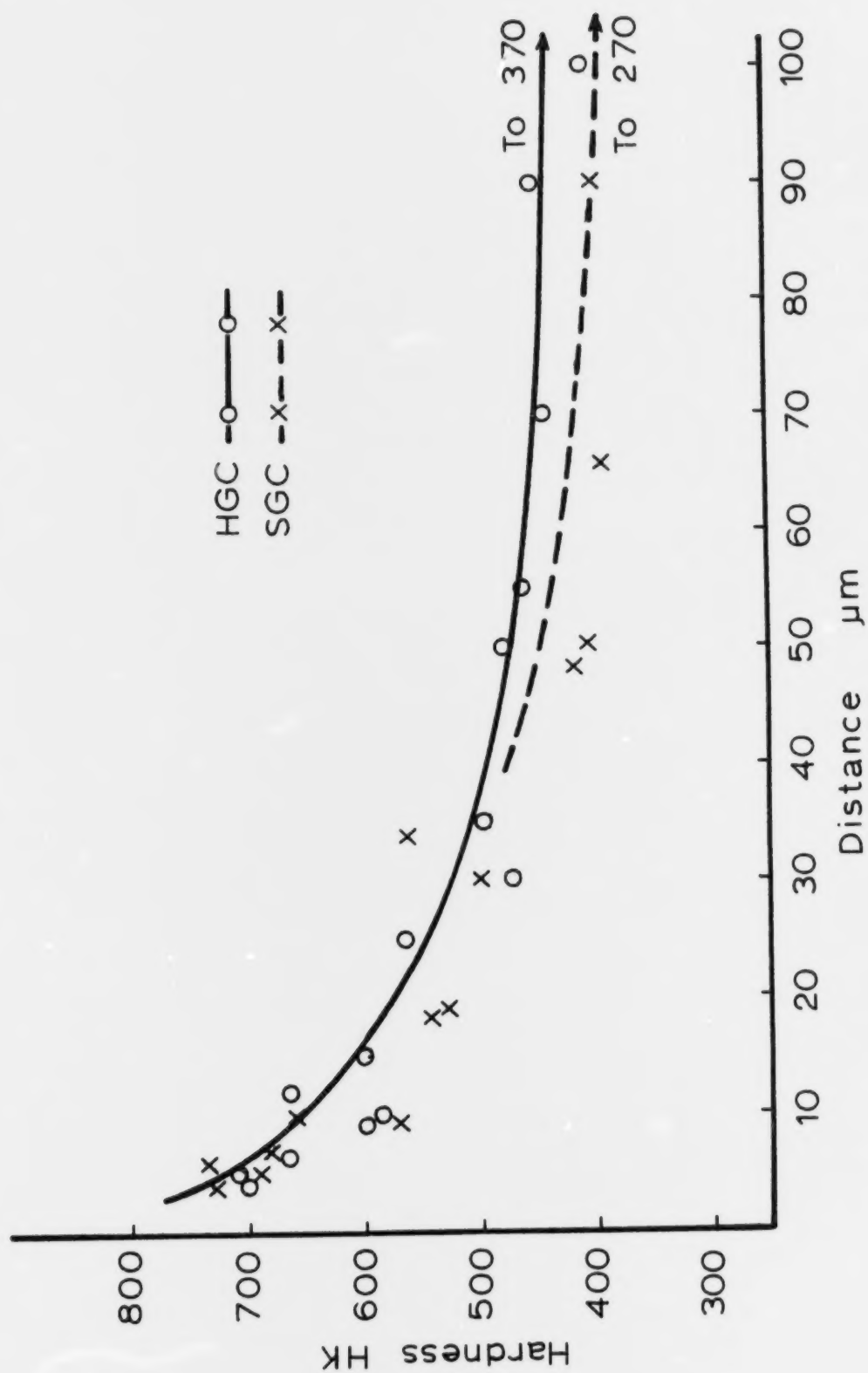


Figure 82. Microhardness vs. distance

For these curves, the bracketed data point in Table 5 has been dropped. Here, d is expressed in nm.

For samples SGC we obtain:

$$HK = 1.43 \times 10^4 d^{-1/2} - 830, \quad r = 0.94 \quad (5.8)$$

$$\text{or, } HK = 7.27 \times 10^4 d^{-1} - 130, \quad r = 0.94 \quad (5.9)$$

$$\text{or, } HK = -4.35 \times 10^3 + 8.67 \times 10^4 d^{-1/2} - 3.70 \times 10^5 d^{-1} \quad (5.10)$$

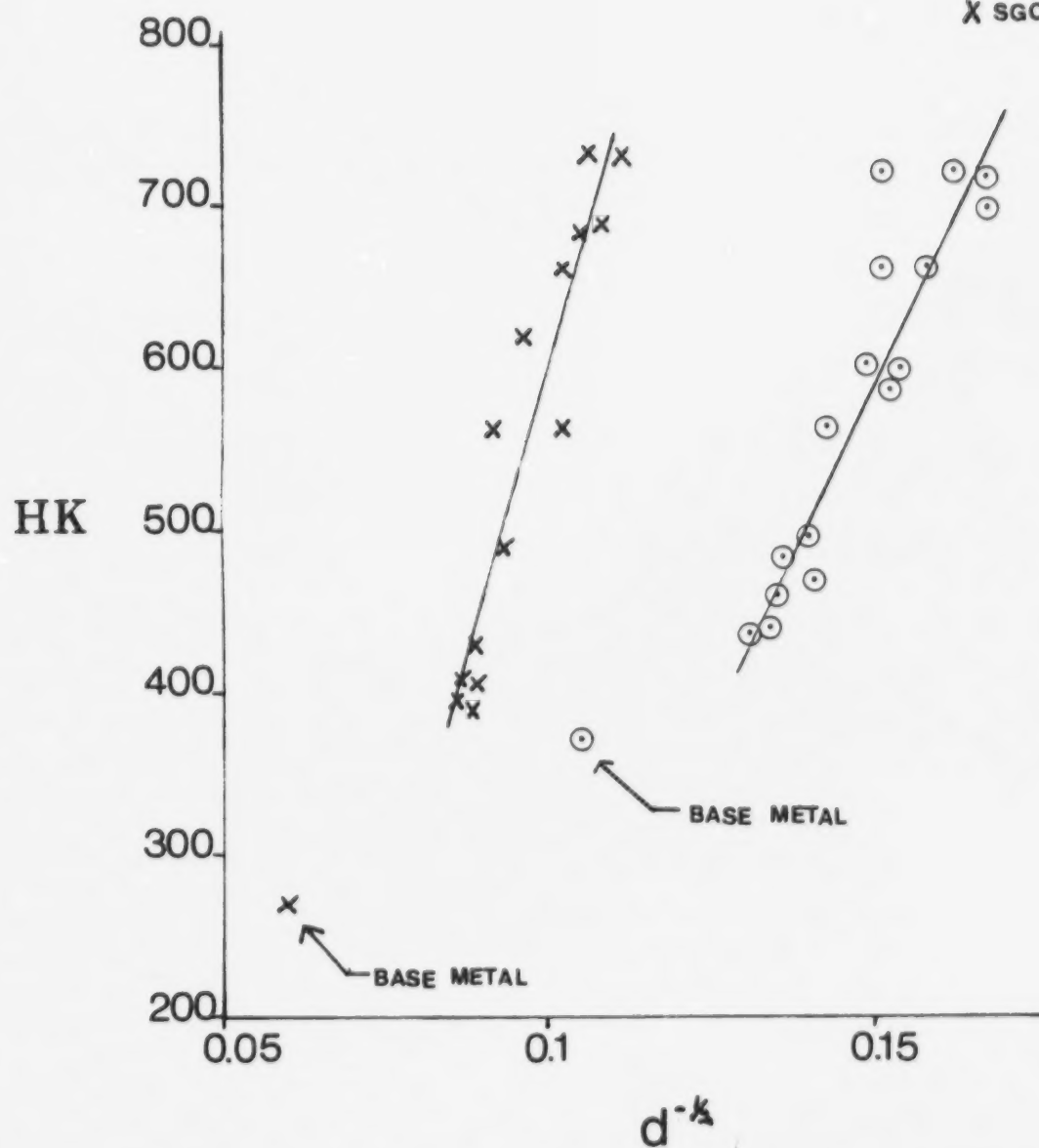
Data points and equations 5.5, 5.6, 5.8 and 5.9 are plotted in Figures 83 and 84. While the fitted equations fairly represent the data within about 100 μm of the wearing surface, they are quite unsatisfying in the following respects:

- i) if the equations are extrapolated to the cementite spacings observed in the base material, the fit is very poor.
- ii) the equations are quite different for samples SGC and HGC, so that it is unlikely that any model relying solely on cementite spacing will be satisfactory.
- iii) the empirical equations all contain negative terms, which are physically meaningless in the Hall-Petch or Langford models.

Basically, the significance of the high values of k and the negative values of a in equations 5.5, 5.6, 5.8 and 5.9 is that near the surface, the increase in hardness with decreasing cementite spacing is much more rapid for fine spacings than for the wider spacings deeper in the metal, so that none of these equations properly describes the variation of hardness with cementite spacing.

○ HGC

X SGC



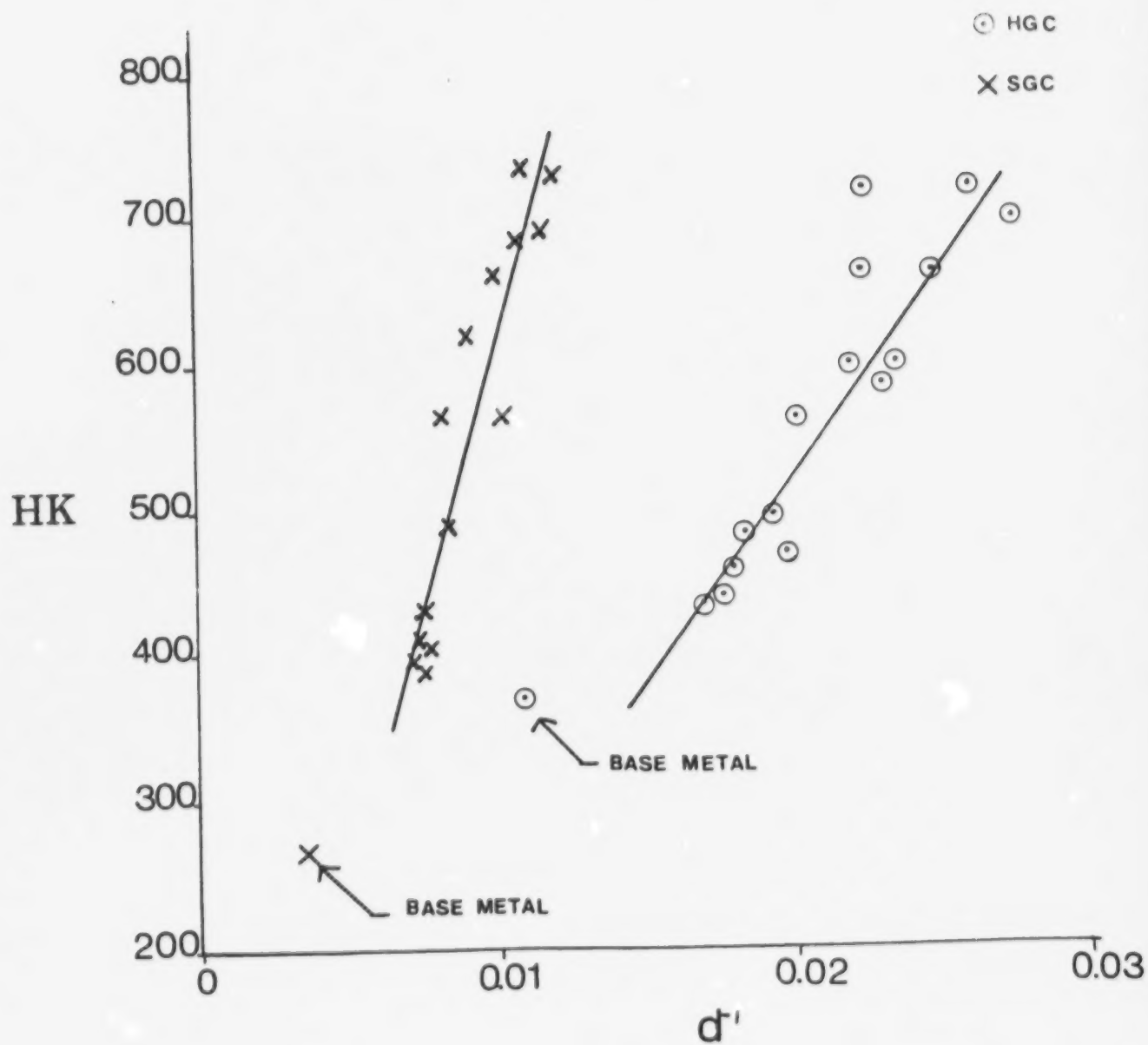


Fig. 34. Microhardness vs (cementite spacing)⁻¹

TABLE 5

Average microhardness, HK, standard deviation and pearlite spacing, d^* , gauge corner samples

Depth, μm	S A M P L E					
	HK	HGC S	d	HK	SGC S	d
4	698	51	36	731	17	81
5	721	41	38	690	28	85
6	-	-		734	-	89
7	662	-	40	684	-	91
9	600	-	42	563	-	96
10	695	124	43	661	42	97
12	662	-	44	-	-	
13	[720]	-	44	-	-	
15	601	-	45	-	-	
18	-	-		620	150	108
25	563	-	49	-	-	
30	470	-	50	490	13	116
35	497	-	51	563	-	119
50	484	12	59	406	23	111
55	461	16	55	-	-	
60	-	-		431	-	128
66	-	-		389	-	130
60 - 80	440	-	56	410	30	131
81 - 100	450	28	58	395	-	135

* Cementite spacings estimated from data shown in Table 4.

A second point of interest is the relationship between the worn microstructure and both microhardness and wear resistance. As seen most clearly in Figure 82, the observed microhardness near the worn surface is essentially the same for samples HGC and SGC. However, the microstructures in these samples are very different. Comparing, for example, Figures 57 and 64, we see that the worn micro-structure of HGC is very fine pearlite, while SGC is coarser pearlite, with many broken lamellae. Table 1 and 3 show also that samples HQ and SQ developed similar hardnesses near the wearing surface. Again, comparing for example Figures 56 and 62, or 69 and 75 or 76 we see that the samples HQ, which started out as finer pearlite have developed a very fine pearlite on wear, while the samples SQ, which were coarser to begin with, developed a less fine structure, containing much broken cementite. These microstructures show quite different wear resistance, even though their hardnesses are the same. Thus, while at this point we do not really understand the wear mechanism, we can conclude that fine pearlite is superior to a coarser, broken pearlite, and that microhardness measurements alone are not a reliable indication of wear resistance, whether we consider microhardness measurements in the new material or in heavily worked worn microstructures.

A third point of interest is the observation that there is very little apparent deformation on the gauge face of either head-hardened or standard rail until distances of less than 50 μm are examined, although the wear, in terms of volume of material lost, is greatest at this region. It is almost as if the metal had been carefully machined away at the gauge face.

A fourth point is the observation that the dislocation density is never very high, except rarely very near the surface, e.g., Figure 70. Consider for instance Figure 28a. Measurements

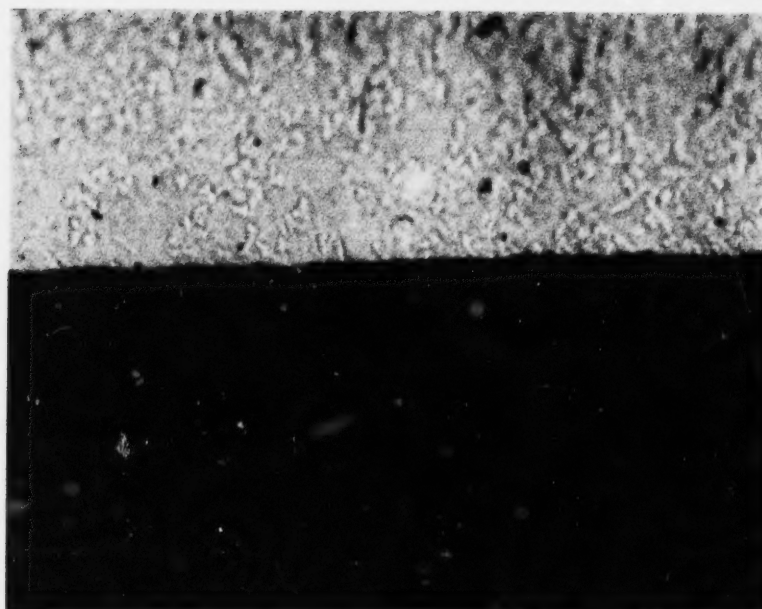
from the micrograph show that there has been local bending to a radius of curvature of about 680 nm. Standard texts on dislocation theory show that the dislocation density required to produce a given radius of curvature is at least:

$$\rho = \frac{1}{br}$$

where ρ is dislocation density, b the Burgers vector and r the radius of curvature. Thus, taking $b = 0.2$ nm, we obtain $\rho = 7.35 \times 10^{11} \text{ cm}^{-2}$. On the micrograph, we should see about 300 dislocations in a 5 mm square area. In fact, we see only a very few dislocations in such an area. We conclude then that dislocations escape from the ferrite. This can only occur by movement of the dislocations out of the ferrite at the ferrite-cementite interface. Physically, this implies slip, or relative movement, of ferrite with respect to the cementite. Also, whatever mechanism or mechanisms are finally responsible for the observed work hardening of the pearlite can not depend on significant accumulations of dislocations for any major component of the hardening.

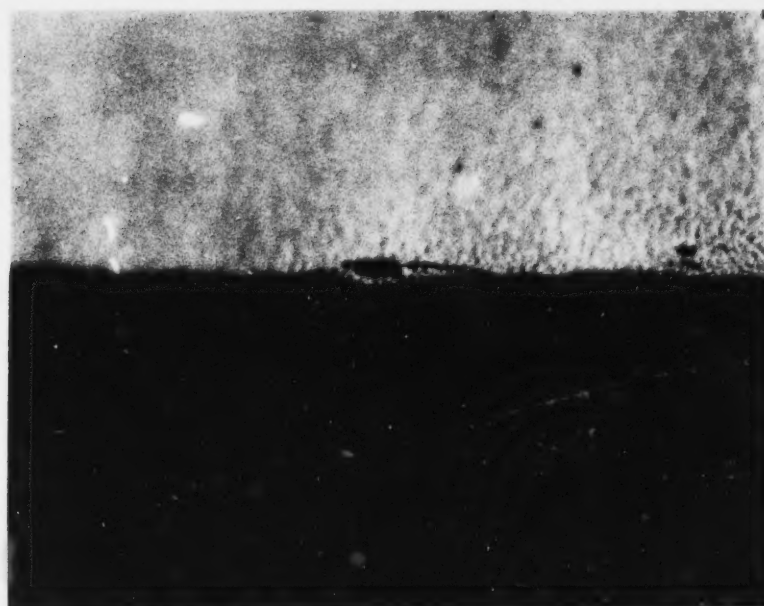
6. REFERENCES

1. Langford, G., "Deformation of Pearlite," Met. Trans. A., 861-875 (1977).
2. Laufer, E.E., and C. MacDonald, Contract Report No. OSU81-00231, December 31, 1983, Section 4.5.
3. Kalousek, J., D.M. Fegredo and E.E. Laufer, "The Wear Resistance and Worn Metallography of Pearlite, Bainite and Tempered Martensite Rail Steel Microstructures of High Hardness," in Wear of Materials 1985, p 212. K.C. Ludema, ed. ASME 1985.
4. Laufer, E.E., and D.M. Fegredo, "A quantitative electron microscopic examination of Nb - and V(C, N) precipitates in eutectoid, premium rail steels transformed under various conditions," C. Met. Q., pp 193-204, 22 (1983).



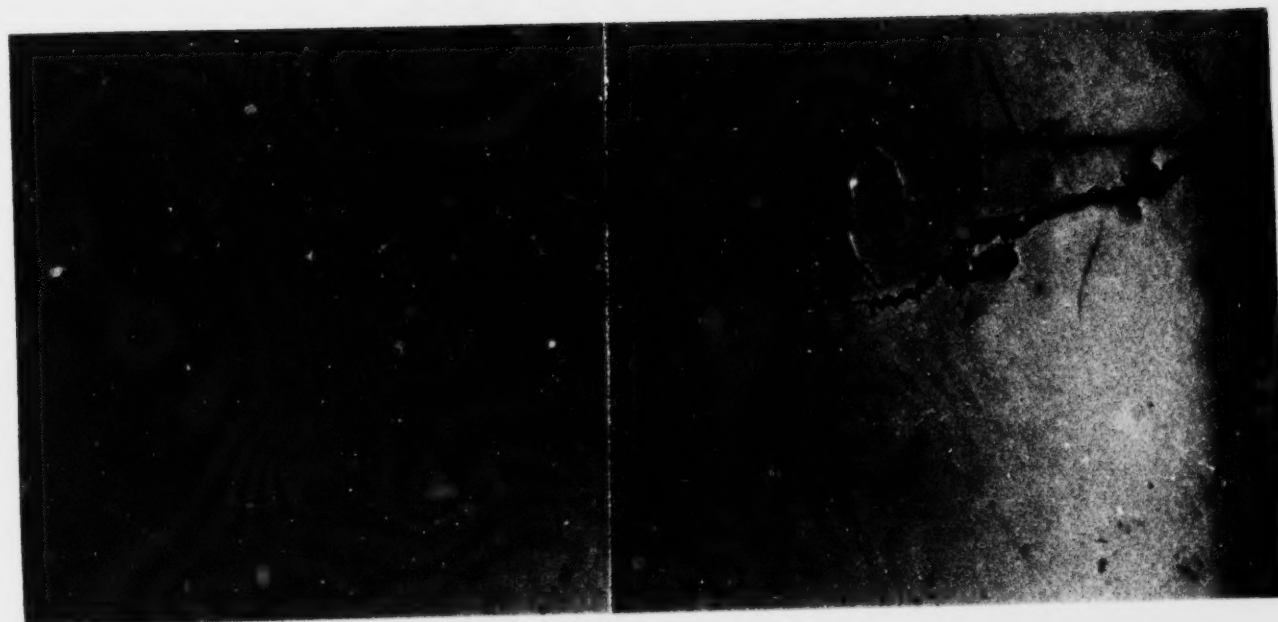
— 20 μ m

Figure 1: Brittle white-etching layer at surface of disc HGF 9PB. Nital etch.



— 20 μ m

Figure 2: Brittle white-etching region and light-etching region on disc HGF 10PC.



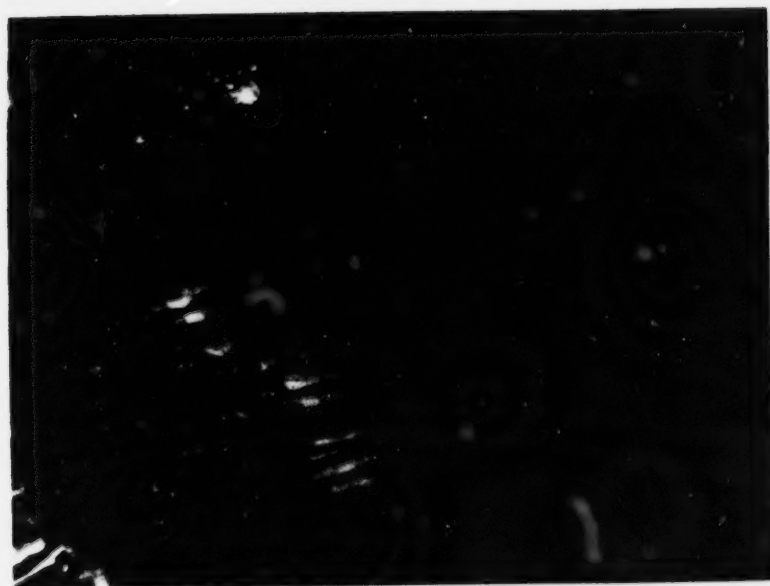
_____ 1mm

Figure 7: Sub-surface cracks, head-hardened rail, half section.



_____ 1mm

Figure 8: Surface cracks, head-hardened rail, quarter section.



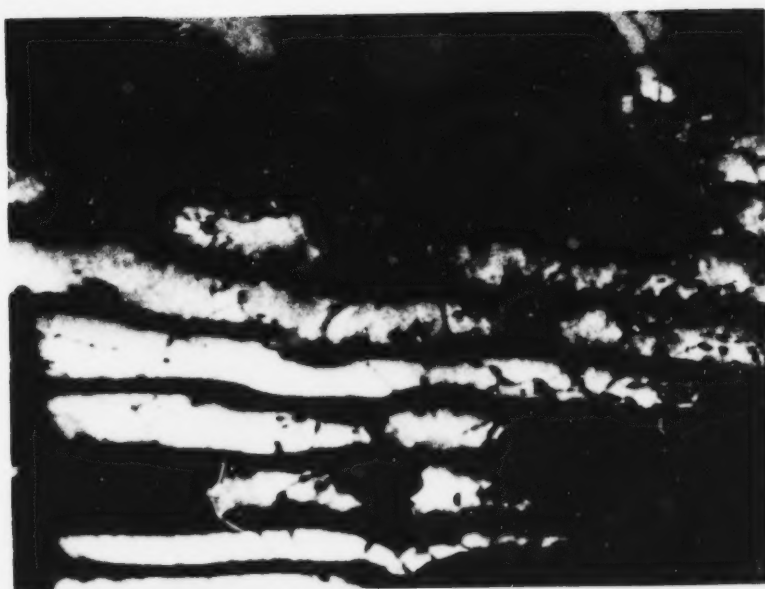
————— 1.0 μ m

Figure 9a: Sample HH, 10 mm (Neg. 3028)



Figure 9b: Diffraction pattern corresponding to figure 9a
(Neg. 3032)

F-5



_____ 0.5 μ m

Figure 9c: Detail of figure 7a (Neg. 3030)

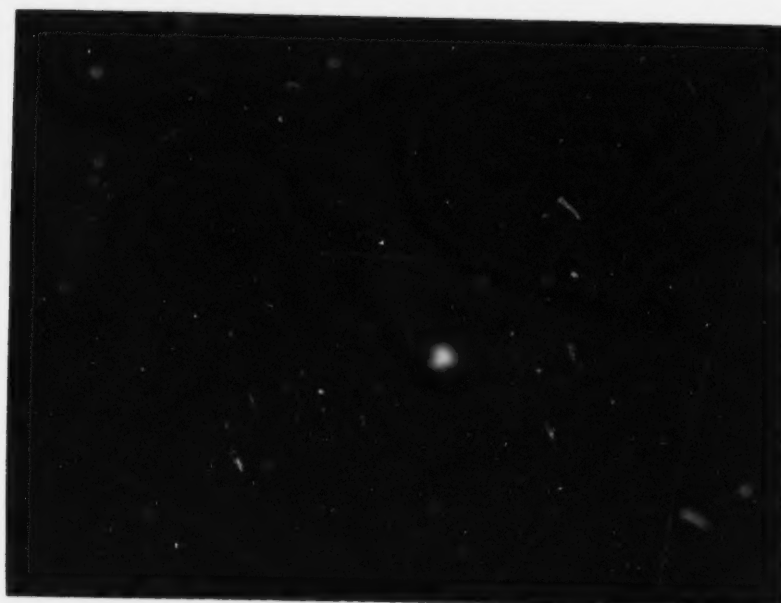


Figure 10a: Sample HQ, 10 mm (Neg 3056).

————— 1.0 μ m



Figure 10b: Diffraction pattern corresponding to figure 10a (Neg. 3058).

F-7

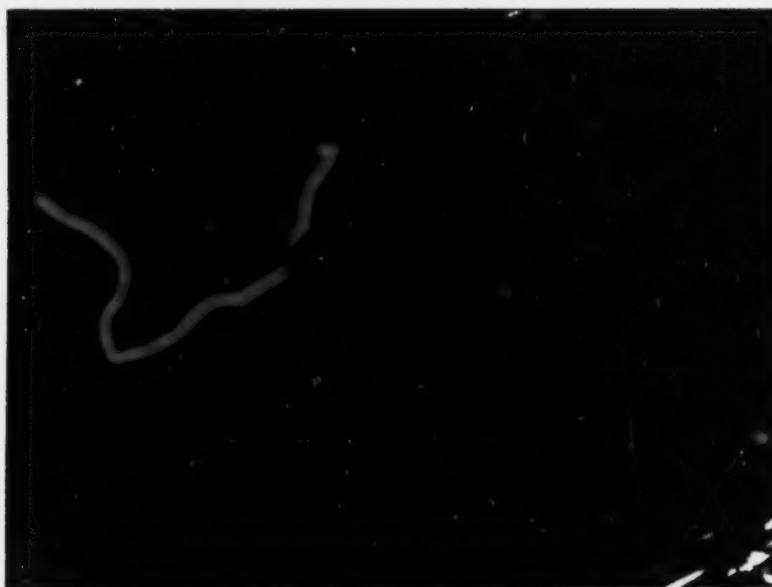


Figure 11a: Sample HGC, 10 mm (Neg. 3087)

1.0 μm

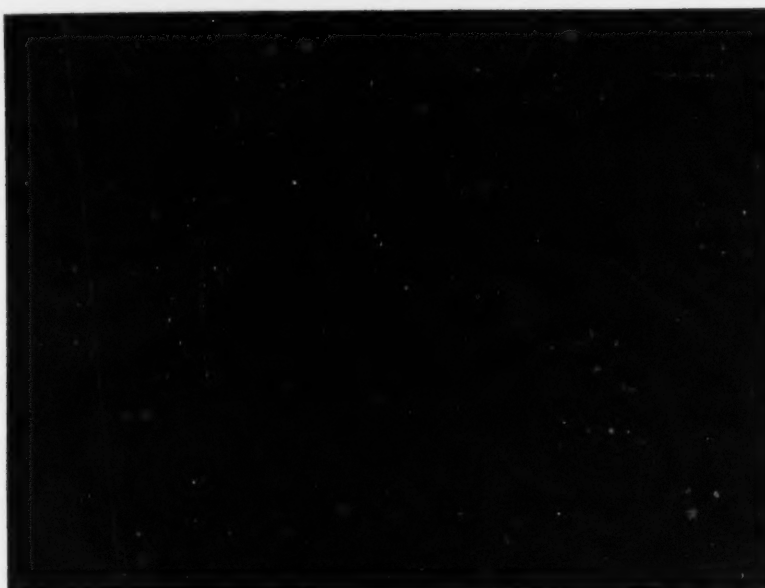


Figure 11b: Diffraction pattern corresponding to figure 11a (Neg. 3088).

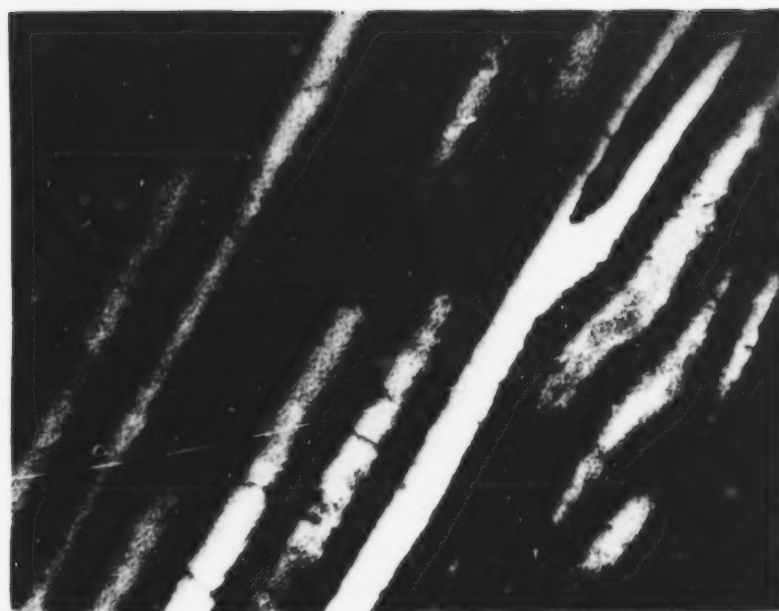


Figure 12a: Sample HGF, 10 mm (Neg 3124).

1.0 μ m



Figure 12b: Diffraction pattern corresponding to figure 12a (Neg. 3125).



————— 1.0 μm

Figure 13a: Sample SH, 10 mm (Neg. 3131).

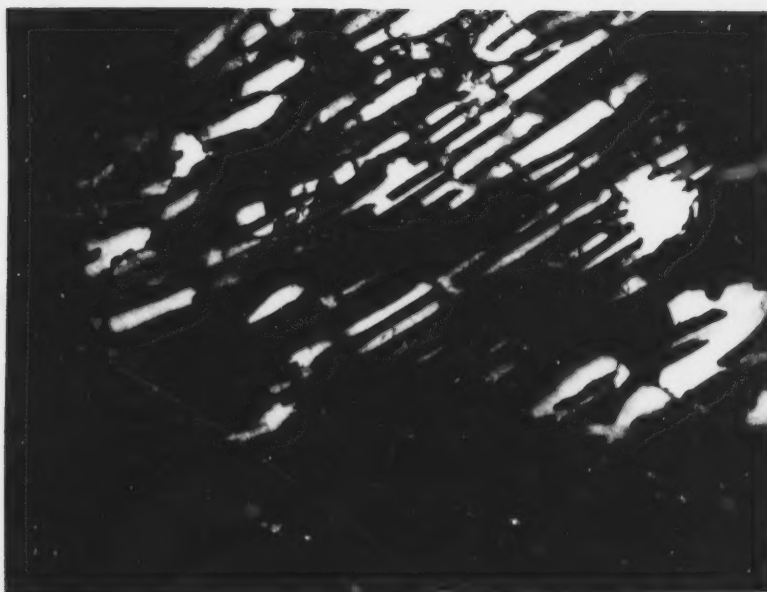


Figure 13b: Diffraction pattern corresponding to figure 13a (Neg. 3132).



1.0 μ m

Figure 14: Sample SH, 10 mm (Neg. 3137)



15a: Sample SQ, 10 mm (Neg. 3137)

————— 1.0 μ m

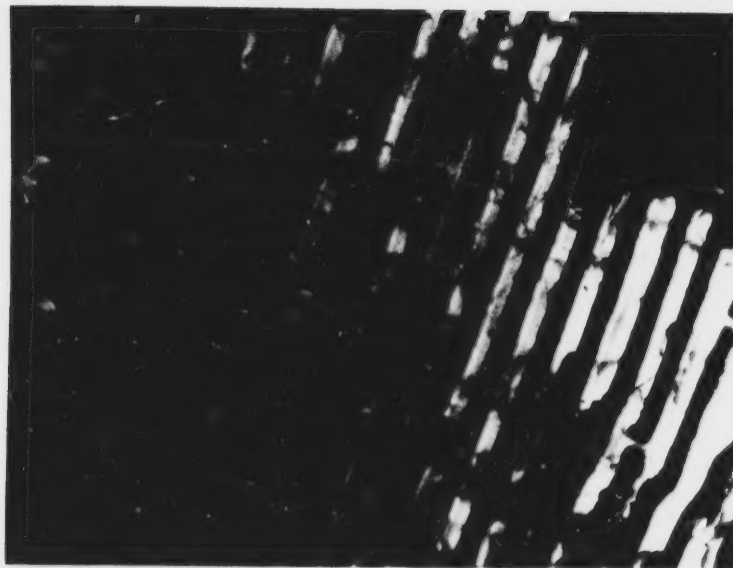


15b: Diffraction pattern corresponding to figure 15a
(Neg. 3177)



— 1.0 μ m

Figure 16 : Sample SQ, 10 mm (Neg. 3179)



1.0 μ m

Figure 17a: Sample SGC, 10 mm (Neg. 3236).



Figure 17b: Diffraction pattern corresponding to figure 15a (Neg. 3237).

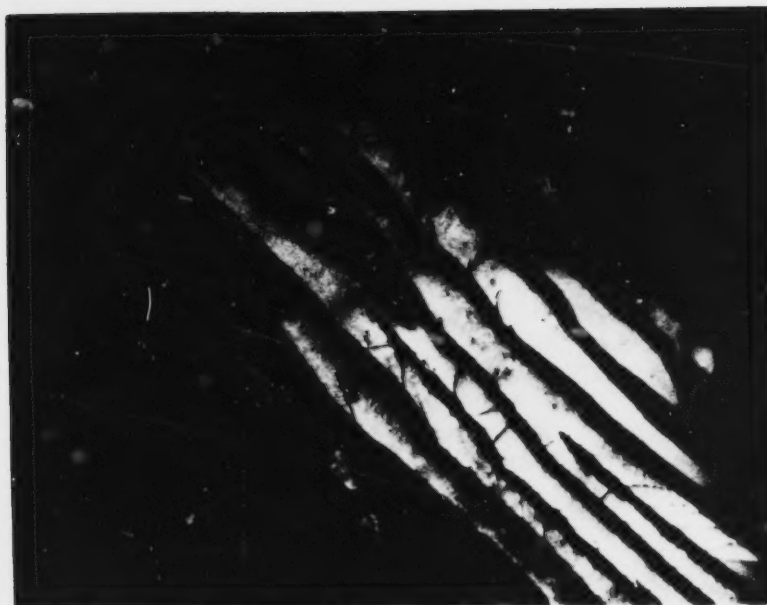


Figure 18a: Sample SGF, 10 mm (Neg 3201).

10 μ m



Figure 18b: Diffraction pattern corresponding to figure 18a (Neg. 3202).

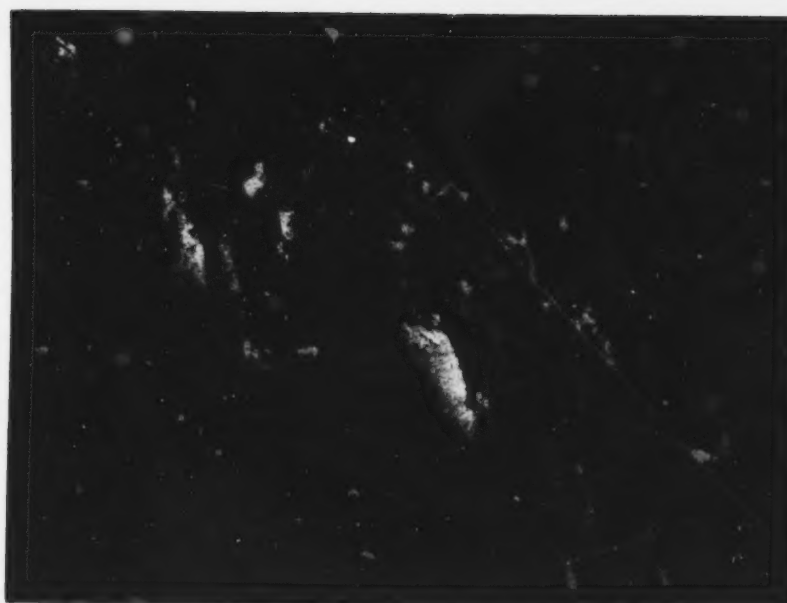


Figure 19a: Sample HH, 1 mm (Neg. 3006)

1.0 μ m



Figure 19b: Diffraction pattern corresponding to figure 19a
(Neg. 3007)



Figure 20: Sample HH, 1 mm (Neg. 3014)

1.0 μ m

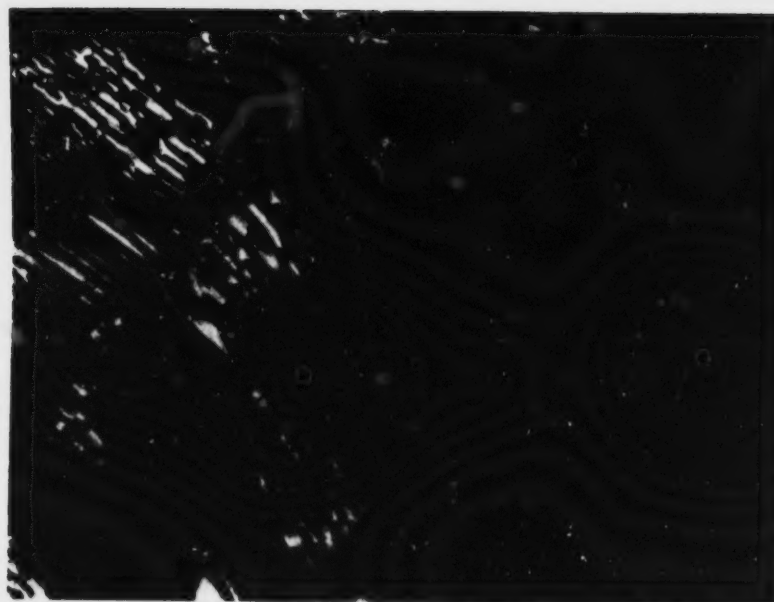


Figure 21a: Sample HQ, 1 mm (Neg. 3037)

1.0 μ m



Figure 21b: Diffraction pattern corresponding to figure 21a.
(Neg. 3038).

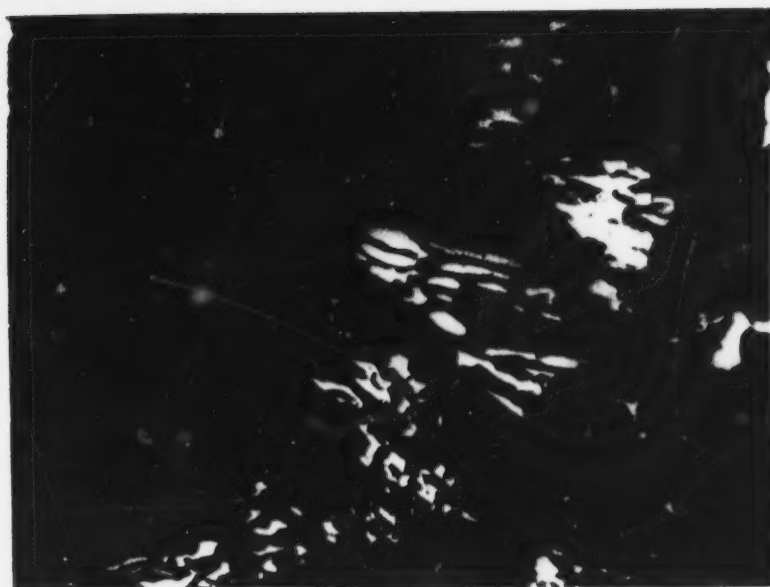


Figure 22: Sample HQ, 1 mm (Neg. 3046)

1.0 μ m



Figure 23a: Sample HGC 1 mm (Neg 3050)

1.0 μ m



Figure 23b: Diffraction pattern corresponding to figure 23a.
(Neg. 3061).



Figure 24: Sample HGC 1 mm (Neg. 3069)

0.5 μ m

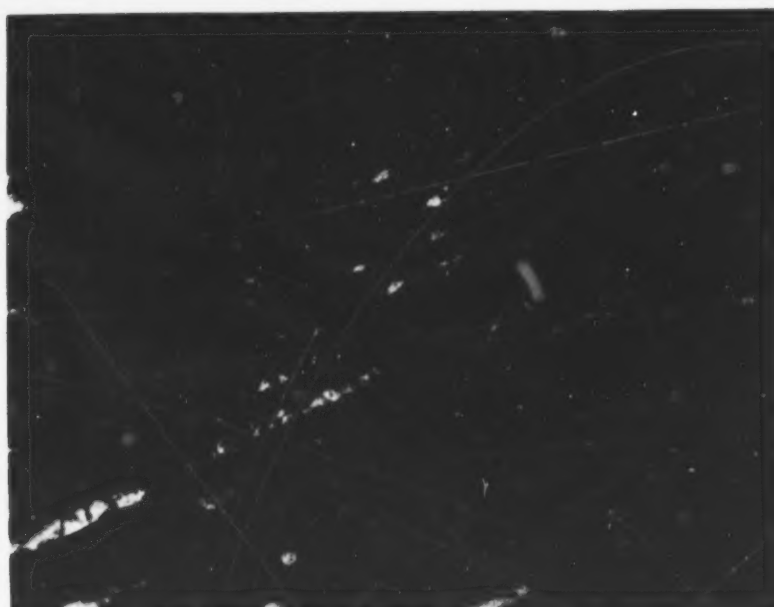


Figure 25: Sample HGC, 1 mm (Neg. 3075)

0.5 μ m



Figure 26a: Sample HGF, 1 mm (Neg. 3091)

1.0 μ m



Figure 26b: Diffraction pattern corresponding to figure 26a.
(Neg. 3092)

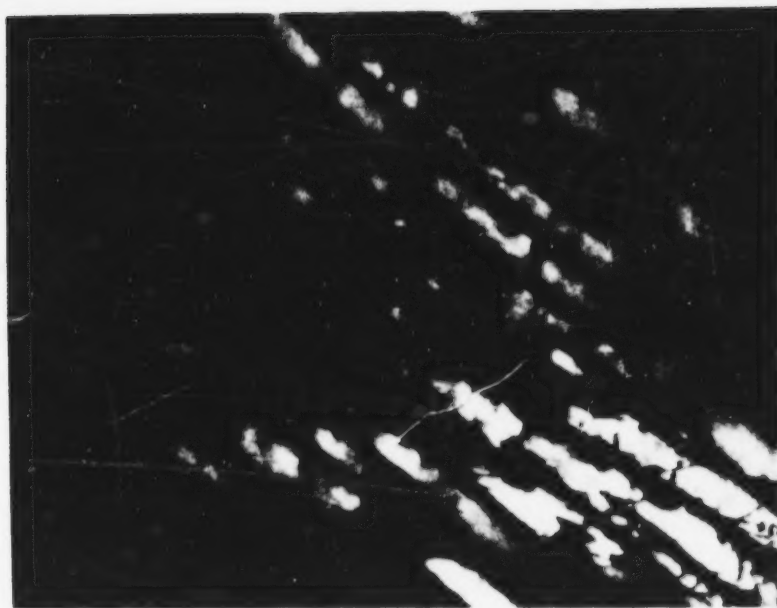


Figure 27: Sample HGF, 1 mm (Neg. 3107)

0.5 μ m



Figure 28a: Sample SH 1 mm (Neg. 3147)

————— 1.0 μ m



Figure 28b: Diffraction pattern corresponding to figure 28a.
(Neg. 3148)



Figure 29: Sample SH 1 mm (Neg. 3159)

————— 1.0 μ m

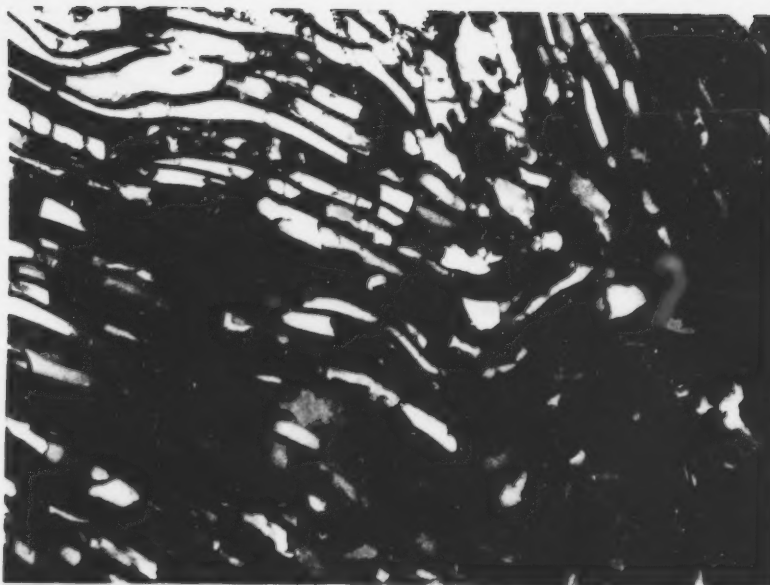


Figure 30a: Sample SQ, 1 mm (Neg. 3187)

2.0 μ m



Figure 30b: Diffraction pattern corresponding to figure 30a.
(Neg. 3186)



Figure 31: Sample SQ, 1 mm (Neg. 3184)

———— 2.0 μ m

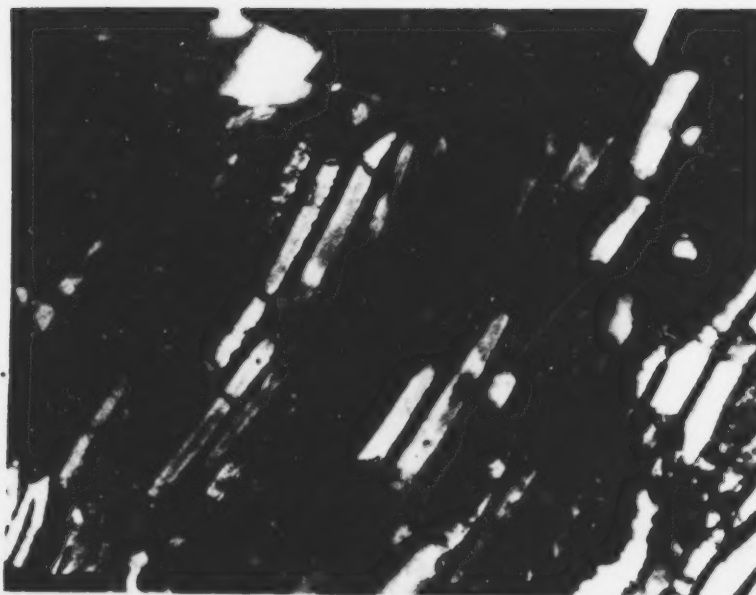


Figure 32a: Sample SGC, 1 mm (Neg. 3222)

———— 1.0 μ m



Figure 32b: Diffraction pattern corresponding to figure 32a. (Neg. 3223).

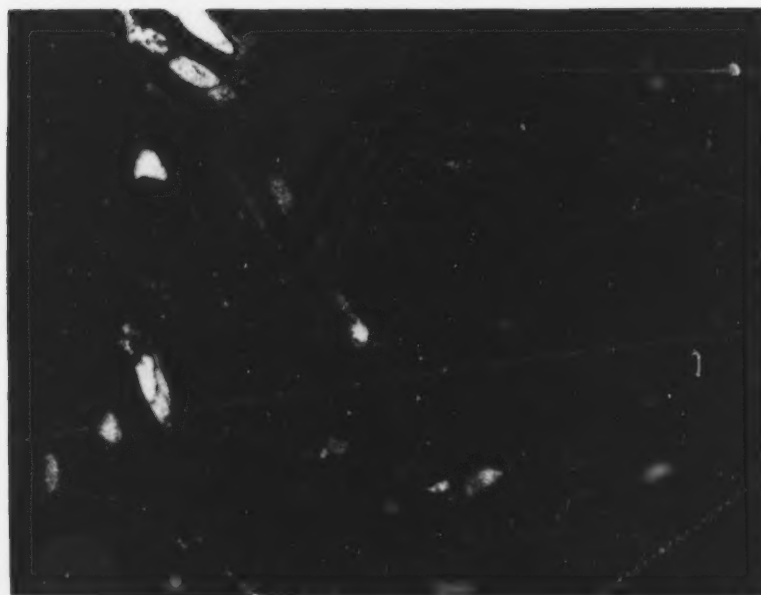


Figure 33a: Sample SGC, 1 mm (Neg. 3226)

————— 1.0 μ m



Figure 33b: Diffraction pattern corresponding to figure 33a.
(Neg. 3227).

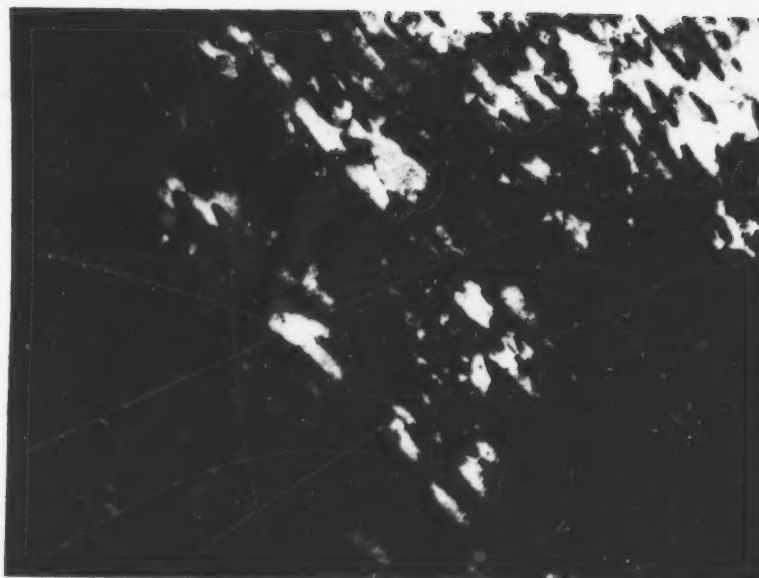


Figure 34a: Sample SGF, 1 mm (Neg. 3212)

————— 1.0 μ m

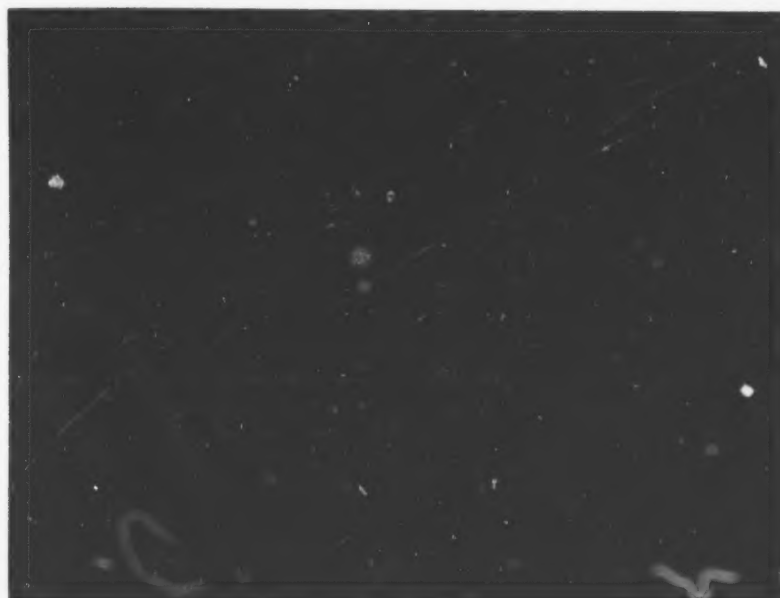


Figure 34b: Diffraction pattern corresponding to figure 34a.
(Neg. 3213).

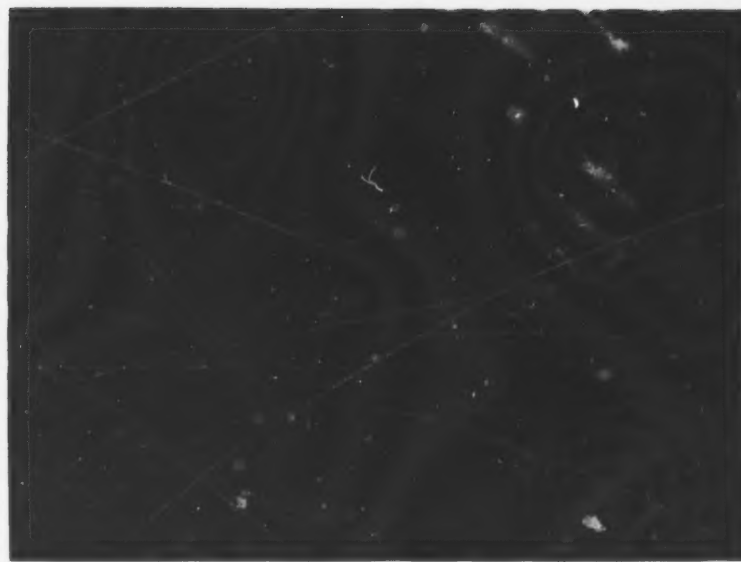
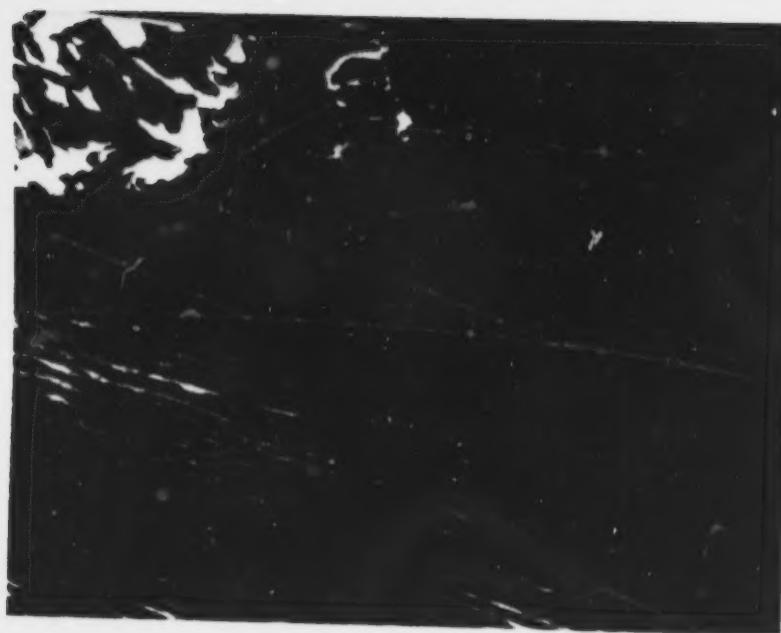


Figure 35: Sample SGF, 1 mm (Neg. 3215)

1.0 μ m



1.0 μm

Figure 36a: Sample HH, 250 um (Neg. 3388)

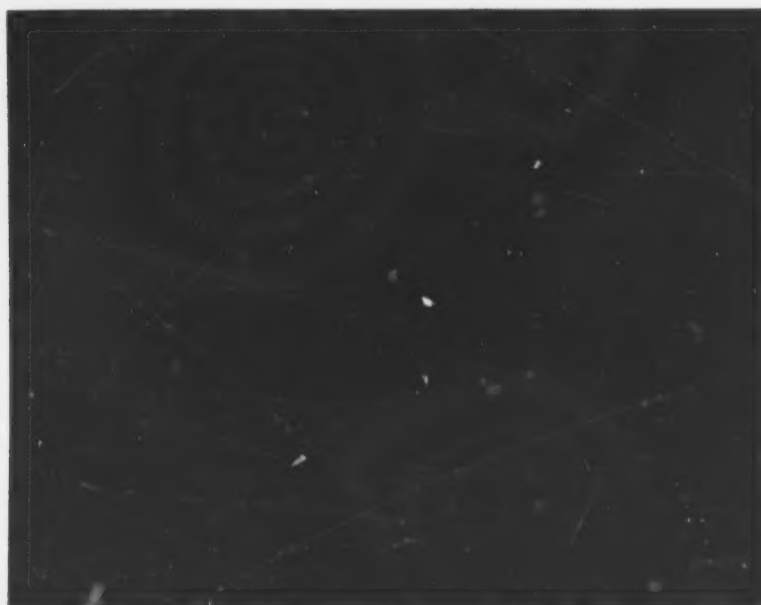


Figure 36b: Diffraction pattern corresponding to figure 36a.
(Neg. 3389)



0.5 μ m

Figure 37: Sample HH, 250 um (Neg. 3390)



Figure 38a: Sample HQ, 250 um (Neg. 3536)

1.0 μ m

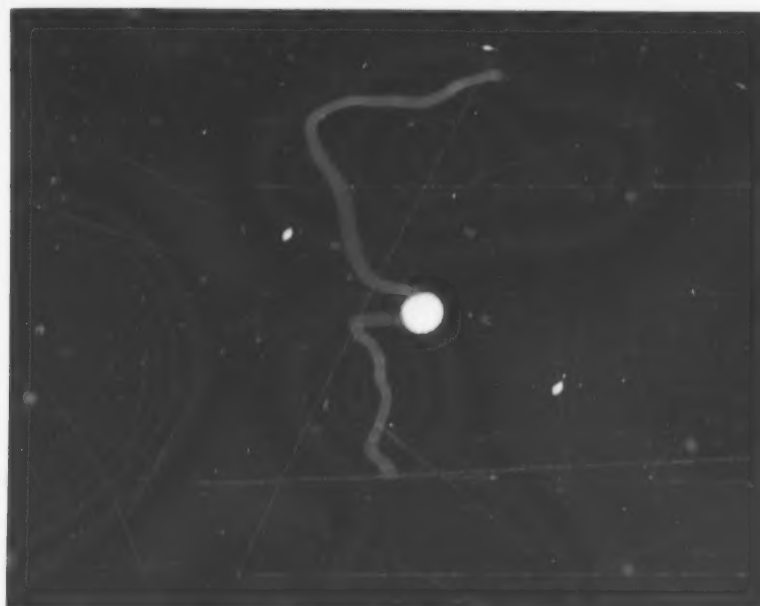


Figure 38b: Diffraction pattern corresponding to figure 38a.
(Neg. 3537)



1.0 μm

Figure 39a: Sample HQ, 250 μm . Bent lamellae are unusual in head-hardened samples. (Neg. 3540)

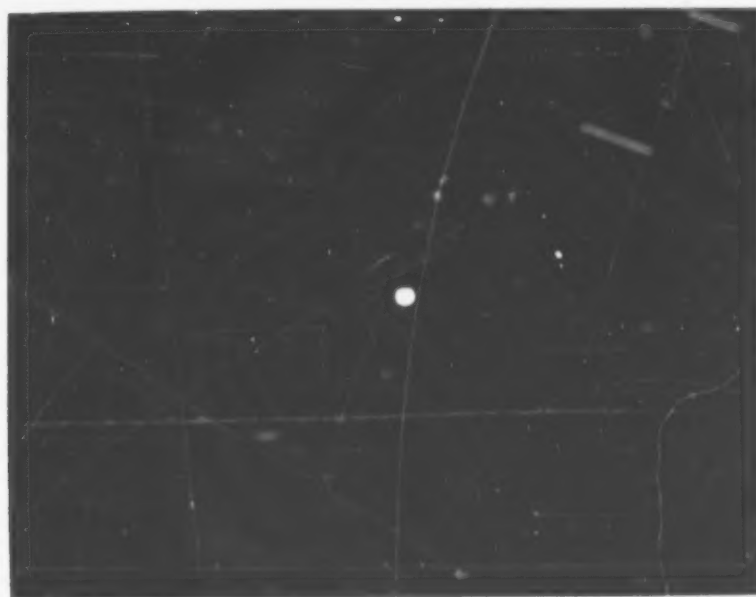


Figure 39b: Diffraction pattern corresponding to figure 39a. (Neg. 3541)

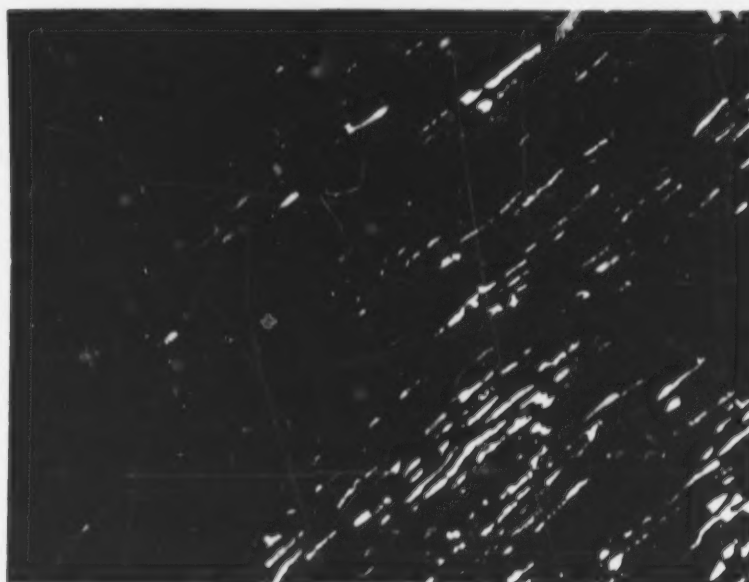


Figure 40a: Sample HGC, 250 um (Neg. 3283)

1.0 μm

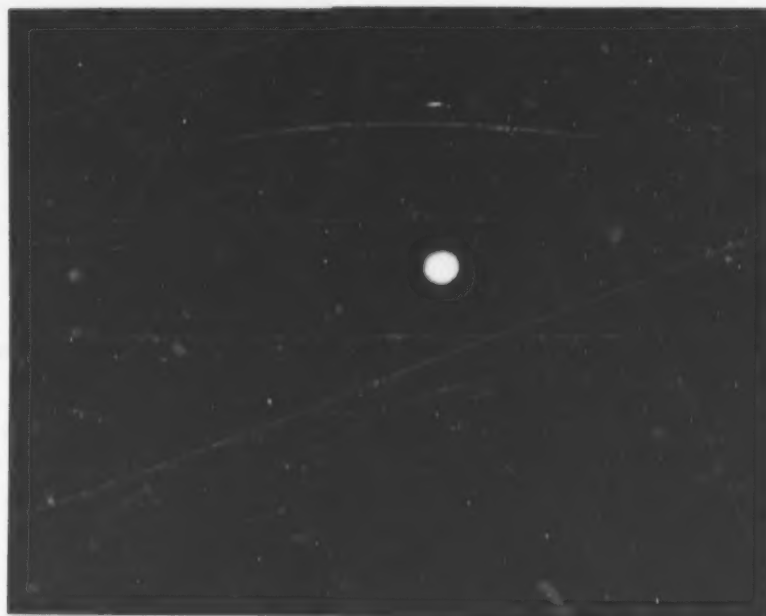
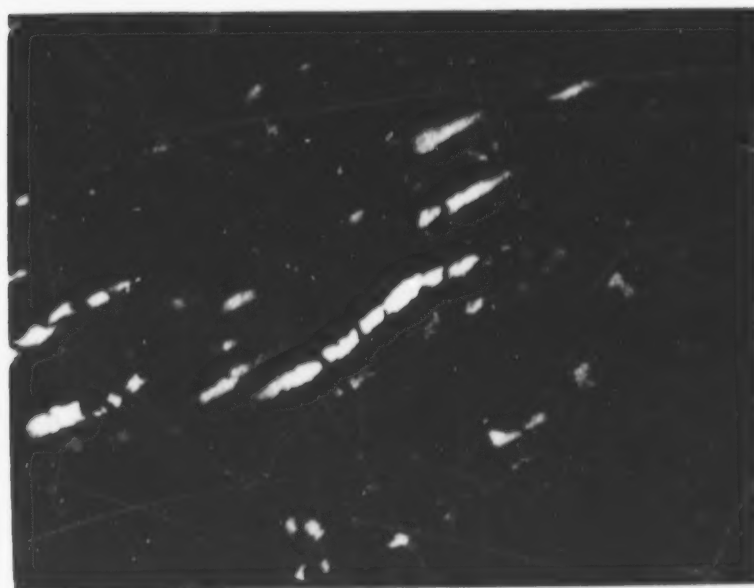
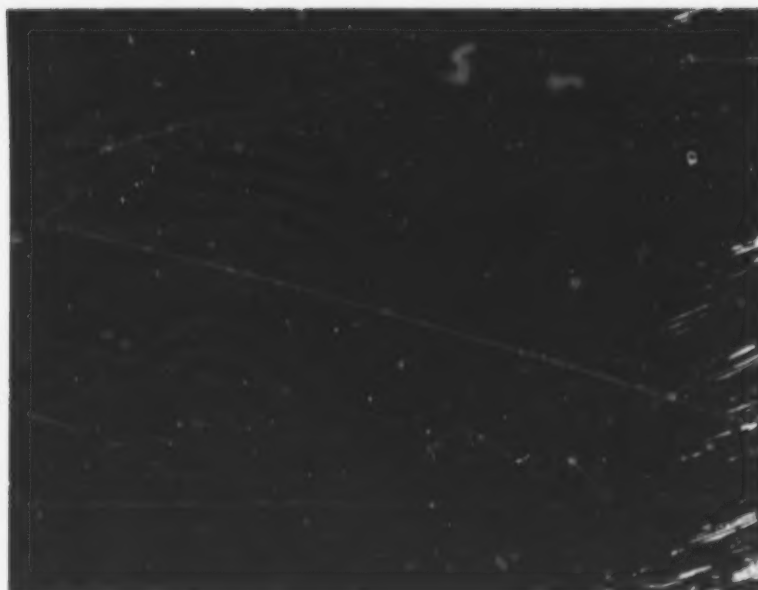


Figure 40b: Diffraction pattern corresponding to figure 40a.
(Neg. 3284)



0.5 μ m

Figure 40c: Detail of figure 40a (Neg. 3285)



— 2.0 μ m

Figure 41: Sample HGF, 250 μ m (Neg. 3317)

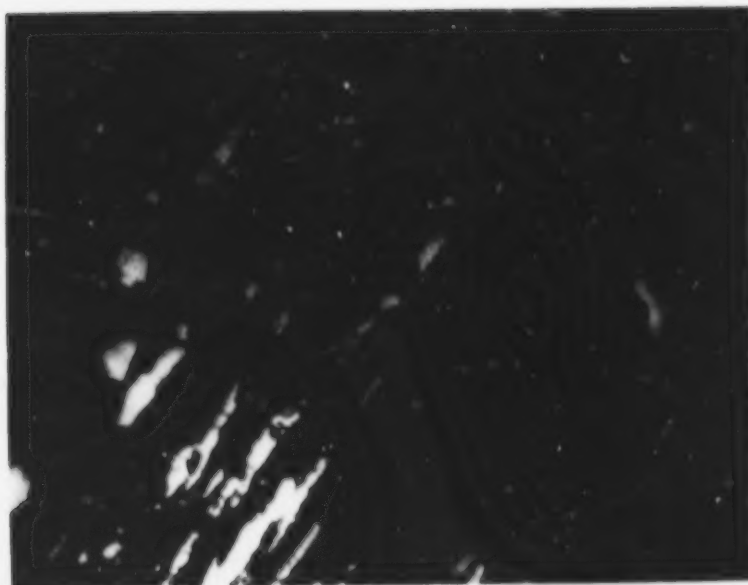


Figure 42a: Sample HGF, 250 um (Neg. 3318)

0.5um



Figure 42b: Diffraction pattern corresponding to figure 42a.
(Neg. 3320)

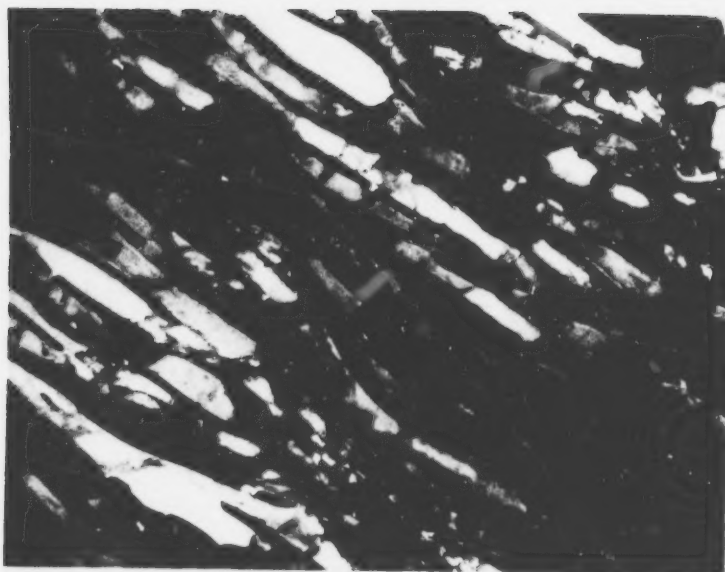


Figure 43a: Sample SH, 250 um (Neg. 3424)

————— 1.0 μ m



Figure 43b: Diffraction pattern corresponding to figure 43a.
(Neg. 3425)

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Figure 44: Sample SH, 250 um (Neg. 3419)

————— 2.0 μ m

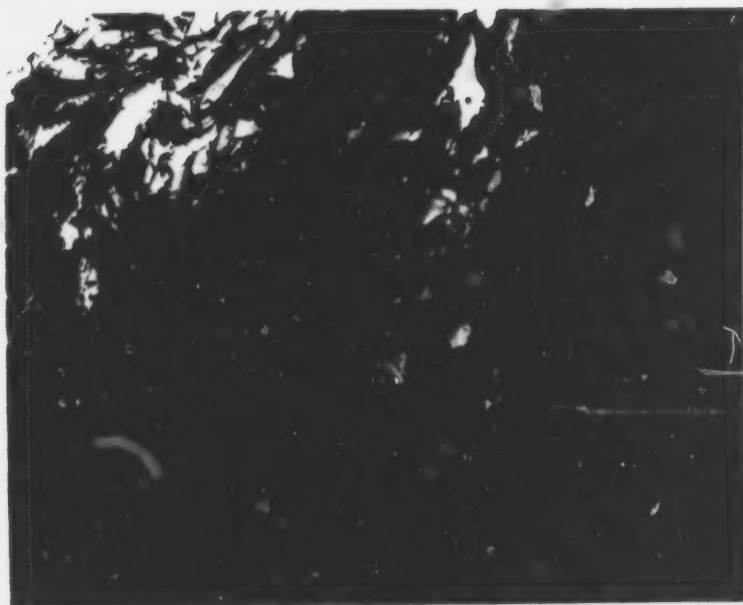


Figure 45a: Sample SQ, 250 um (Neg. 3430)

1.0 μ m

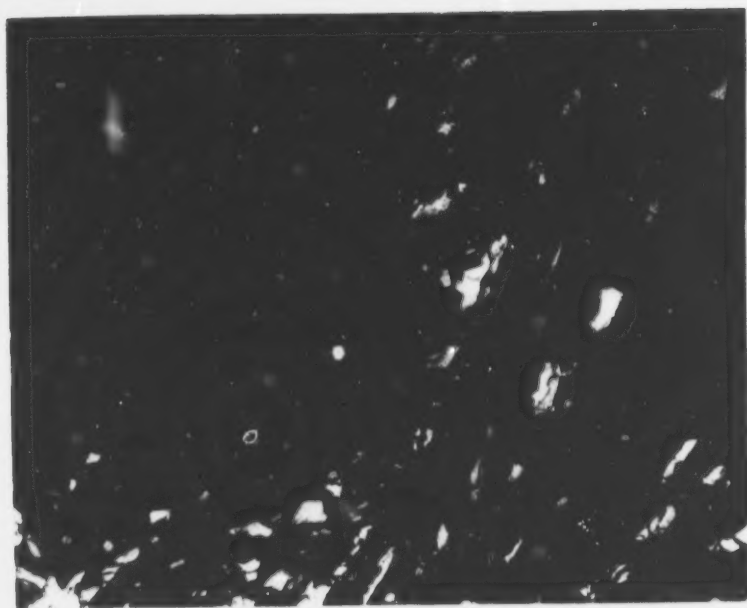


Figure 45b: Diffraction pattern corresponding to figure 45a.
(Neg. 3431)



2.0um

Figure 46: Sample SQ, 250 um (Neg. 3469)



2.0um

Figure 47: Sample SQ, 250 um (Neg. 3470)

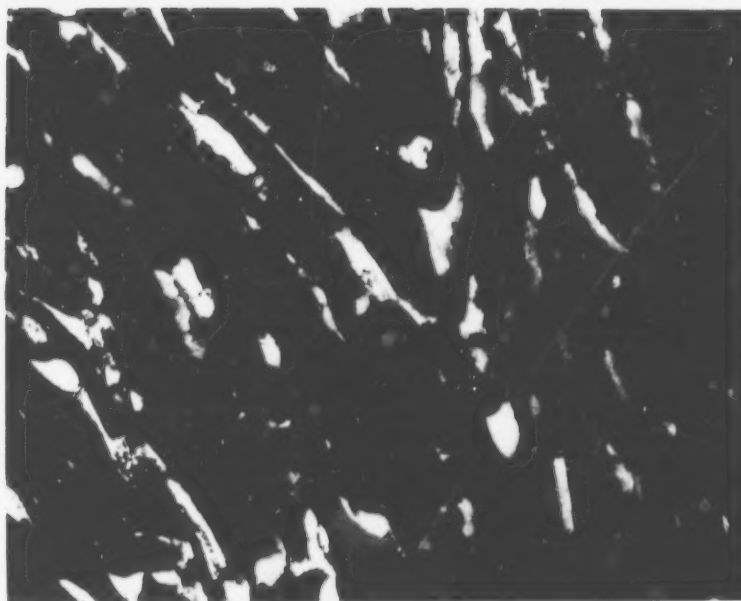


1.0 μ m

Figure 48a: Sample SGC, 250 um (Neg. 3441)



Figure 48b: Diffraction pattern corresponding to figure 48a.
(Neg. 3442)



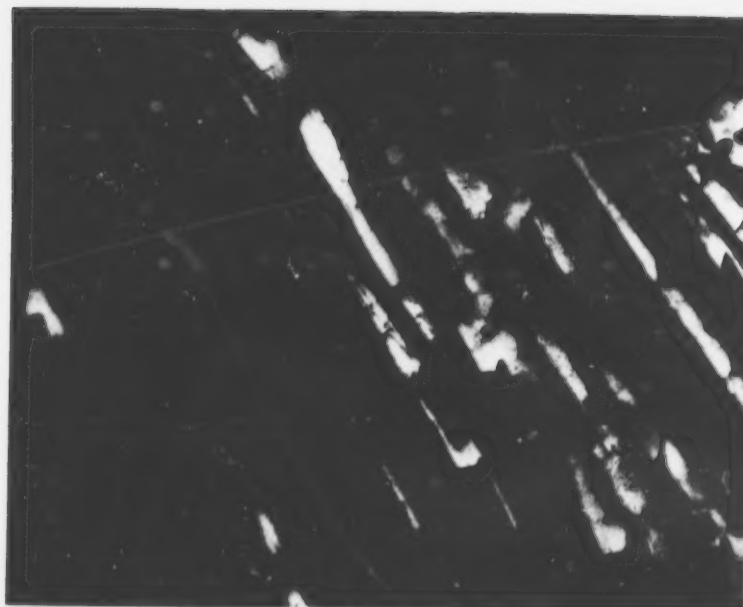
1.0 μ m

Figure 49: Sample SGC, 250 um (Neg. 3443)



1.0 μ m

Figure 50: Sample SGC, 250 um (3445)

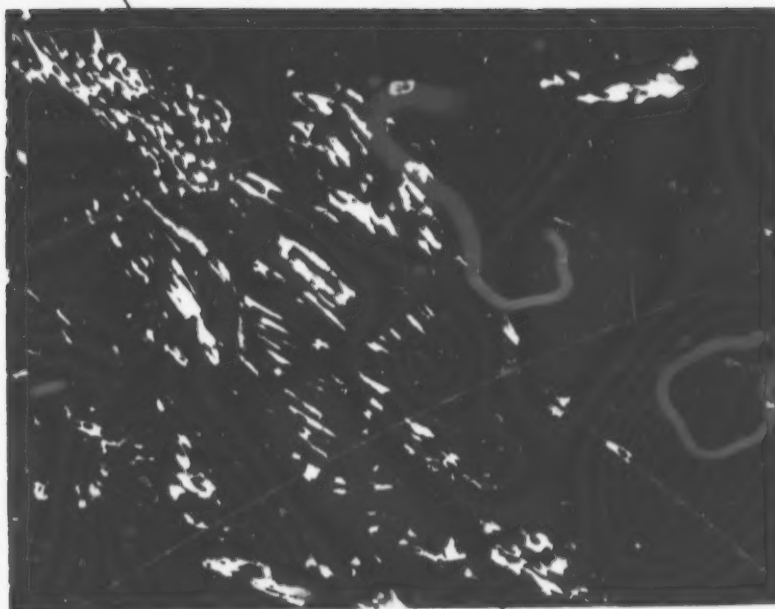


1.0 μm

Figure 51a: Sample SGF, 250 um (Neg. 3436)



Figure 51b: Diffraction pattern corresponding to figure 51a.
(Neg. 3437)



1.0 μ m

Figure 52a: Sample HH, 50 um (Neg. 3524)

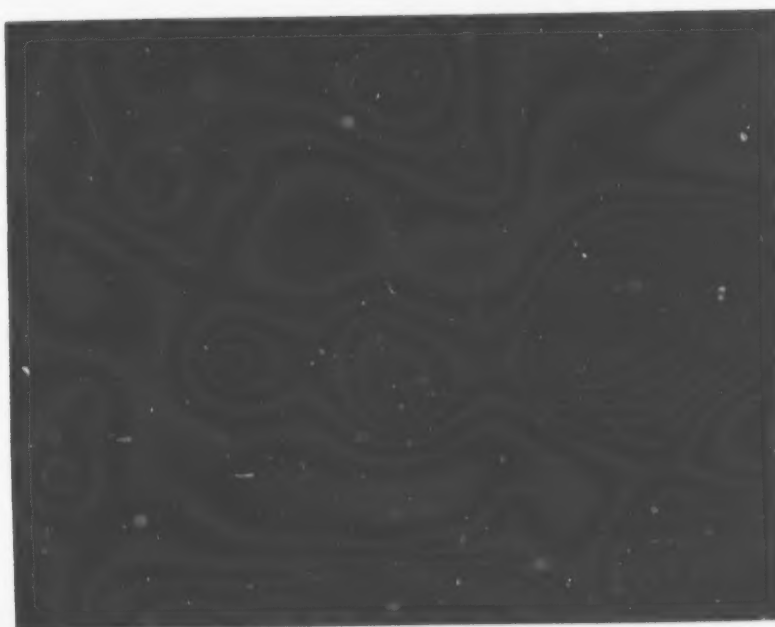


Figure 52b: Diffraction pattern corresponding to figure 52a.
(Neg. 3525)

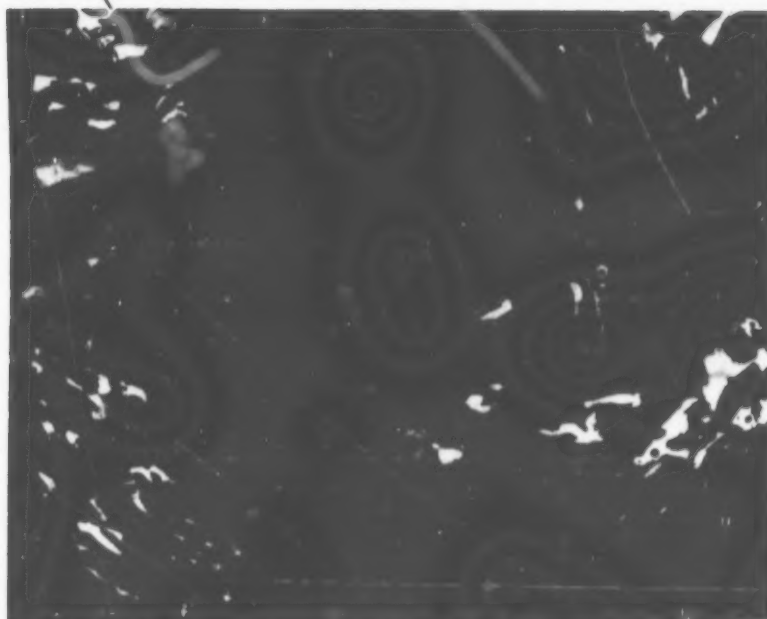


Figure 53a: Sample HH, 50 um (Neg. 3526)

1.0 μ m

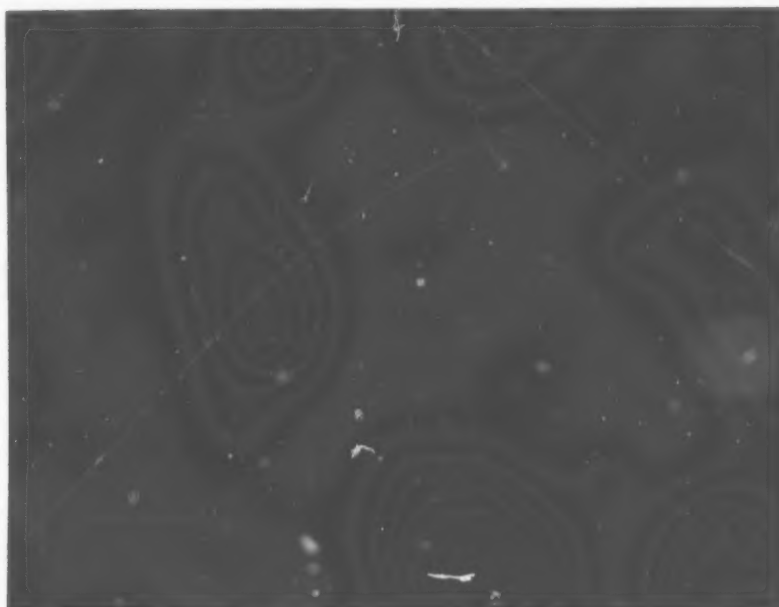
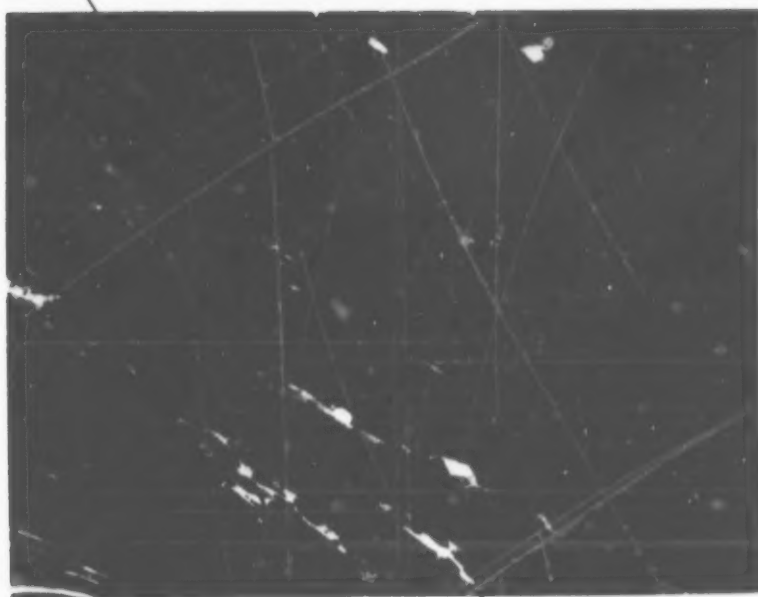


Figure 53b: Diffraction pattern corresponding to figure 53a.
(Neg. 3527)

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1.0 μm

Figure 54a: Sample HQ, 50 um (Neg. 3401)



Figure 54b: Diffraction pattern corresponding to figure 54a.
(Neg. 3404)



Figure 55a: Sample HQ, 50 um (Neg. 3399)

1.0 um

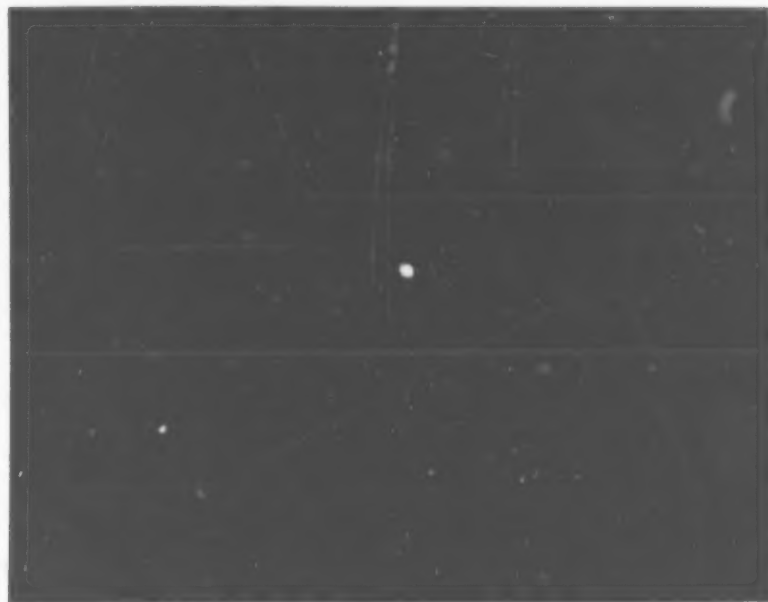
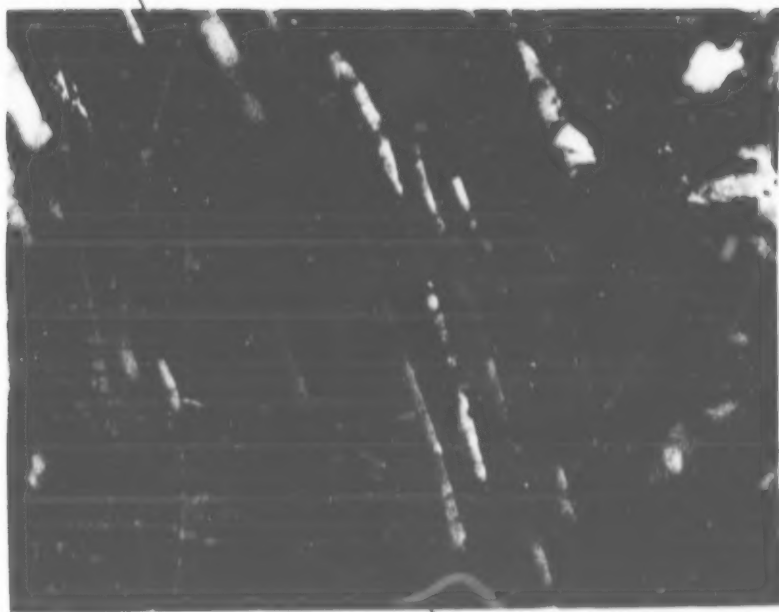


Figure 55b: Diffraction pattern corresponding to figure 55a.
(Neg. 3400)

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0.5 μ m

Figure 56: Sample HQ, 50 um (Neg. 3509)

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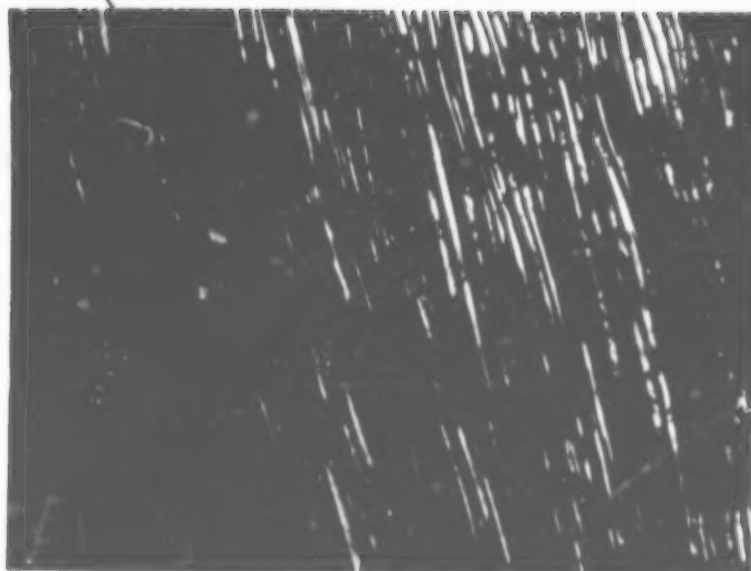


Figure 57a: Sample HGC, 50 um (Neg. 3592)

1.0 μ m

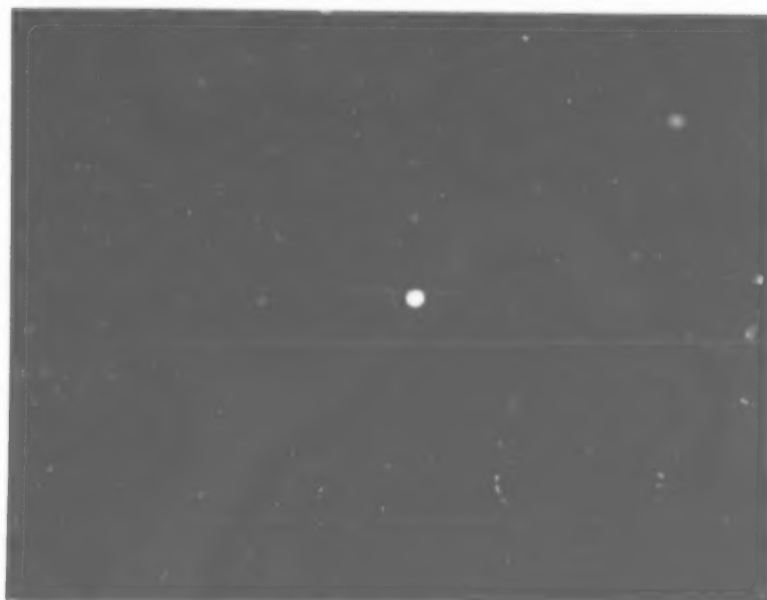


Figure 57b: Diffraction pattern corresponding to figure 57a.
(Neg. 3591)

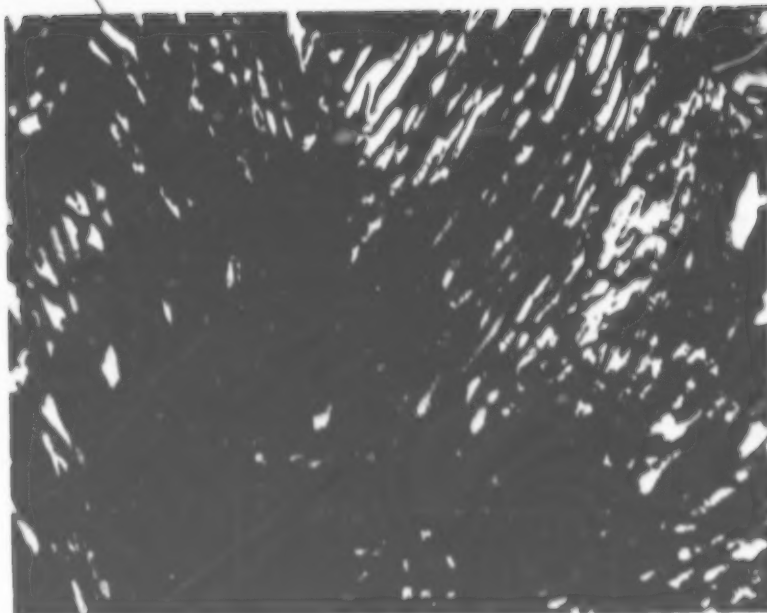


Figure 58a: Sample HGF, 50 um (Neg. 3483)

1.0 μ m

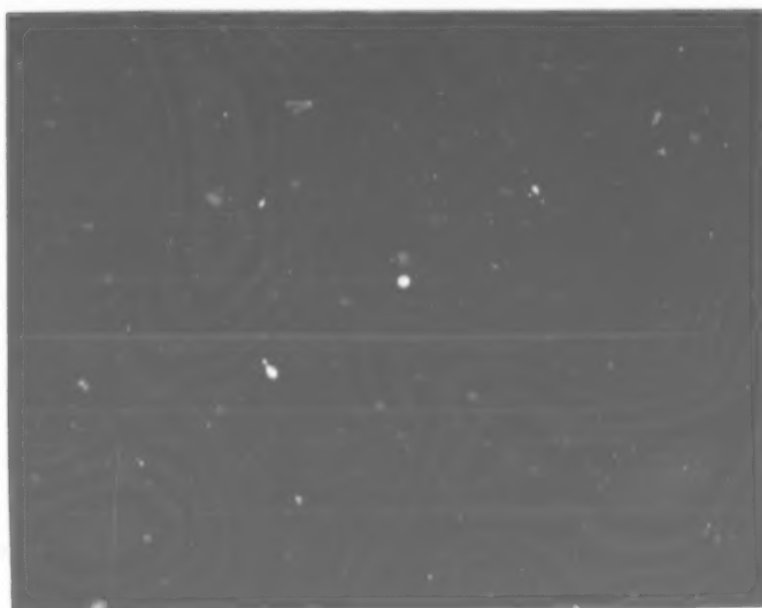


Figure 58b: Diffraction pattern corresponding to figure 58a.
(Neg. 3484)

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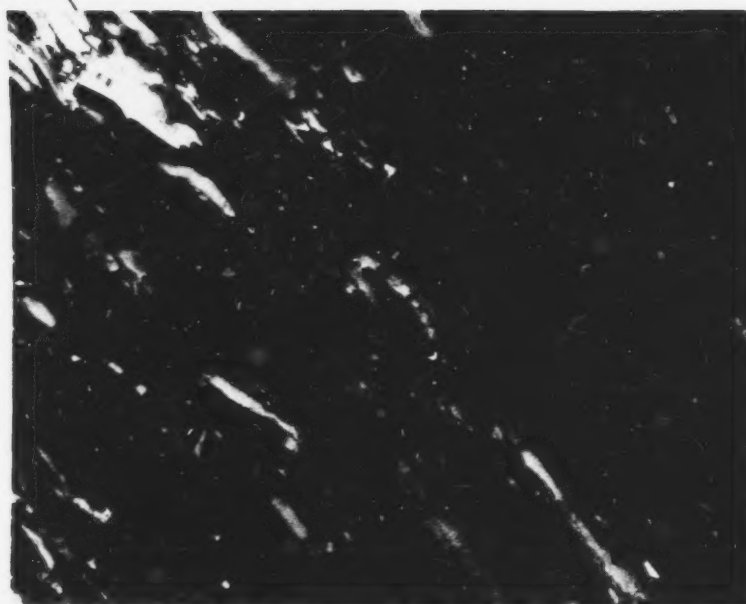


Figure 59a: Sample SH, 50 um (Neg. 3488)

1.0 μ m



Figure 59b: Diffraction pattern corresponding to figure 59a.
(Neg. 3489)

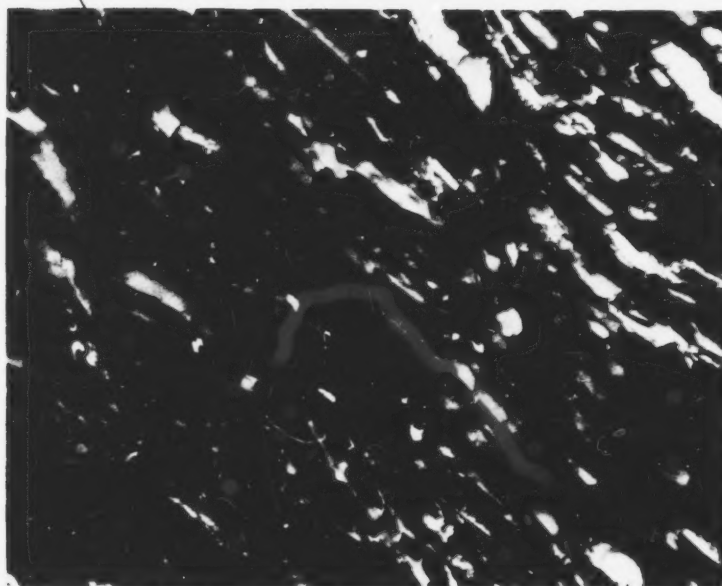


Figure 60a: Sample SH, 50 um (Neg. 3492)

1.0 μ m



Figure 60b: Diffraction pattern corresponding to figure 60a.
(Neg. 3493)



Figure 61a: Sample SQ, 50 um (Neg. 3455)

1.0 μ m



Figure 61b: Diffraction pattern corresponding to figure 61a.
(Neg. 3456)

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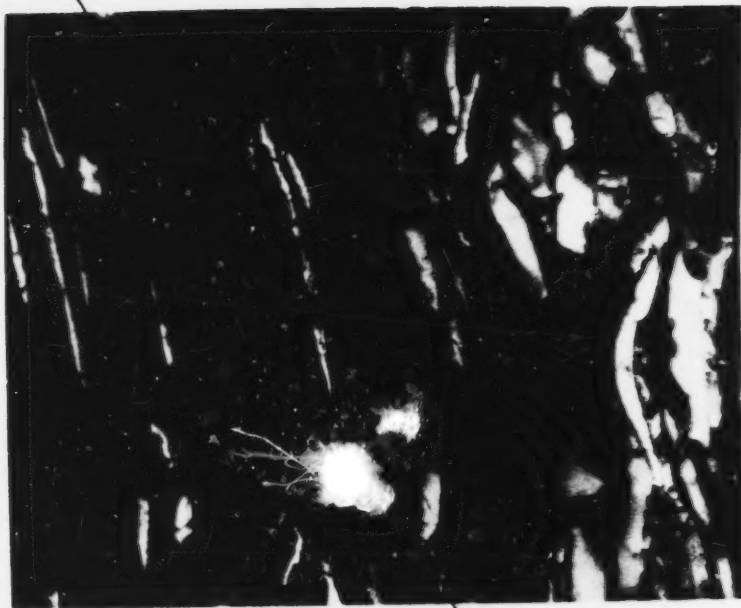


Figure 62: Sample SQ, 50 um (Neg. 3451)

1.0 μ m

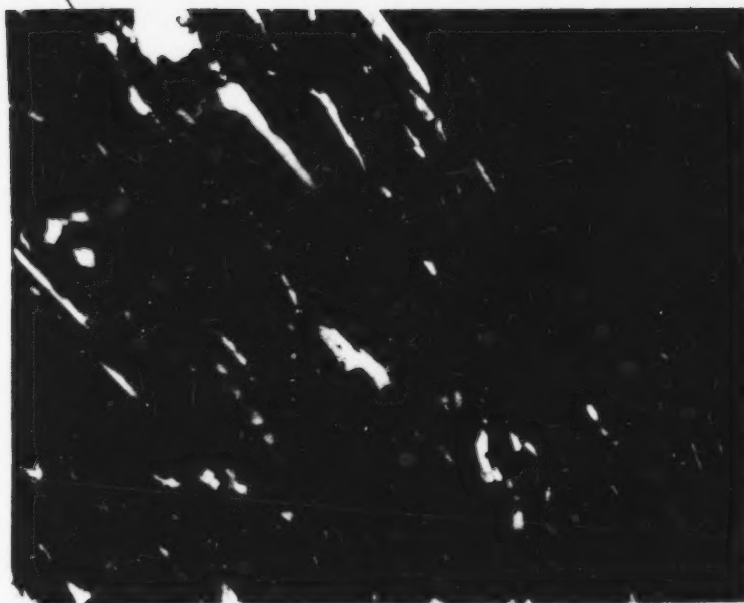


Figure 63a: Sample SGC, 50 um (Neg. 3273)

_____ 1.0 μ m



Figure 63b: Diffraction pattern corresponding to figure 63a.
(Neg. 3277)

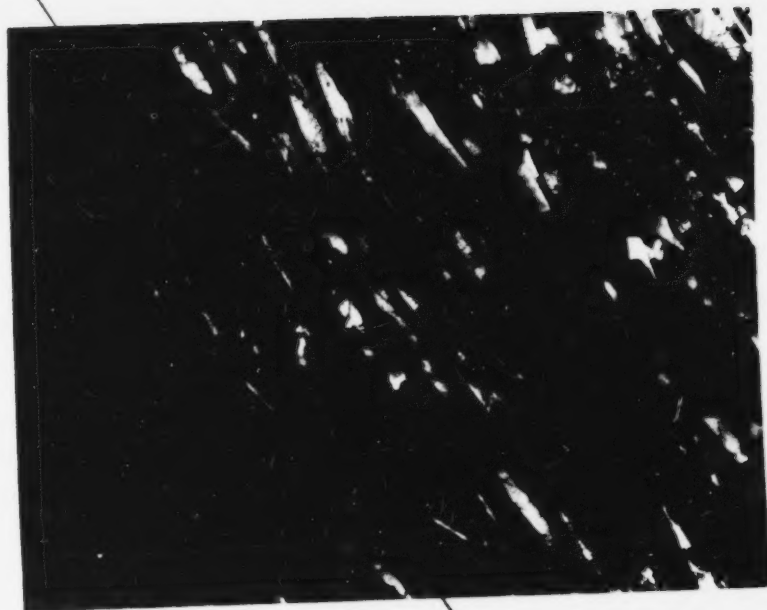


Figure 64: Sample SGC, 50 um (Neg. 3498)

1.0 μ m

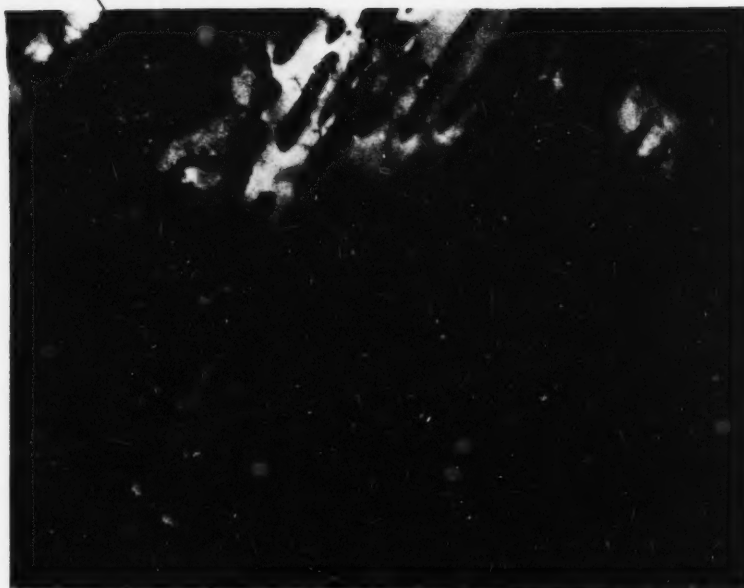


Figure 65a: Sample SGF, 50 um (Neg. 3331)

1.0 μ m



Figure 65b: Diffraction pattern corresponding to figure 65a.
(Neg. 3332)

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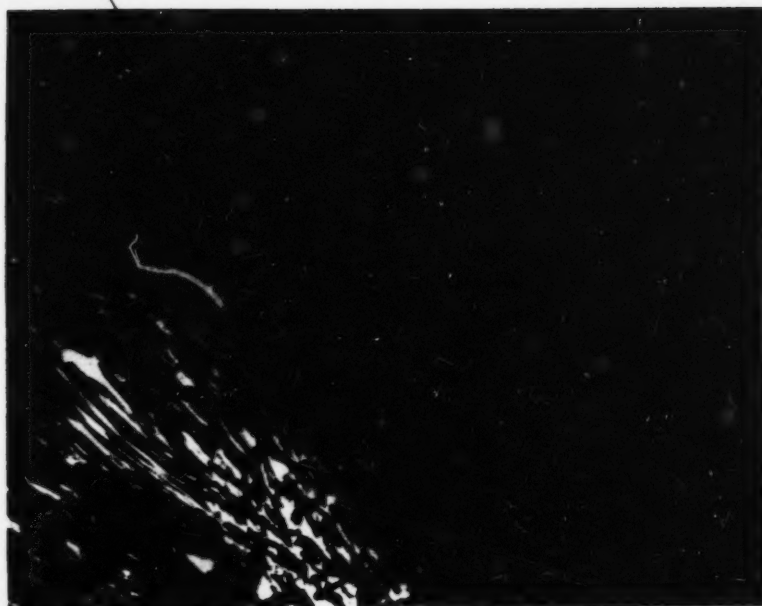


Figure 66a: Sample HH, 24 um (Neg. 3384)

1.0 μm



Figure 66b: Diffraction pattern corresponding to figure 66a.
(Neg. 3385)

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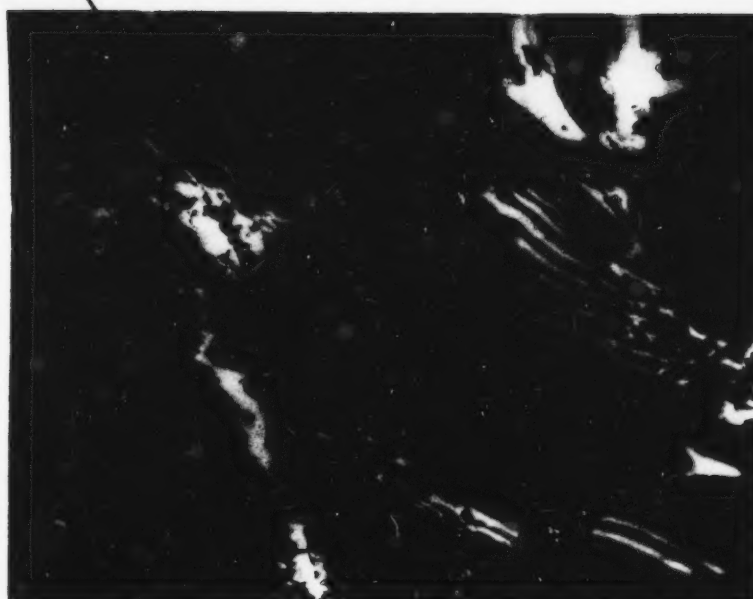


Figure 67a: Sample HH, 24 um (Neg. 3386)

————— 1.0 μ m

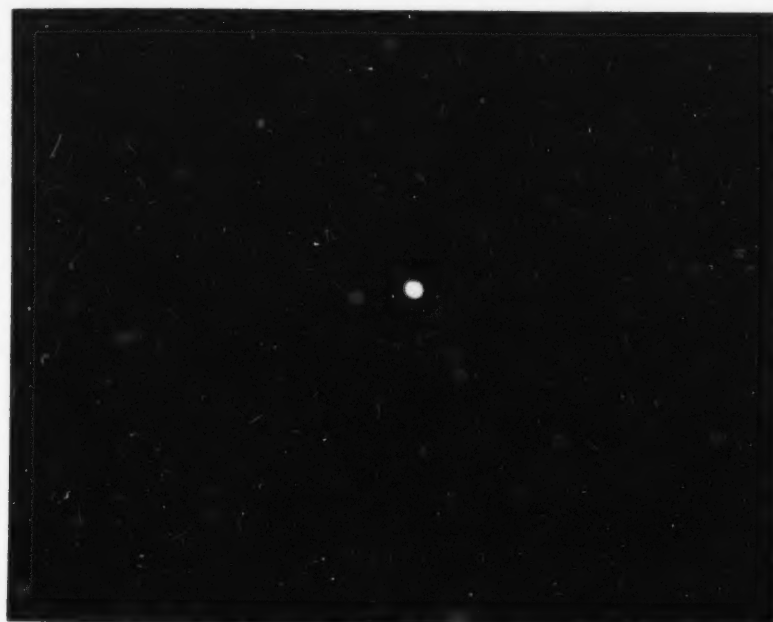


Figure 67b: Diffraction pattern corresponding to figure 67a.
(Neg. 3387)

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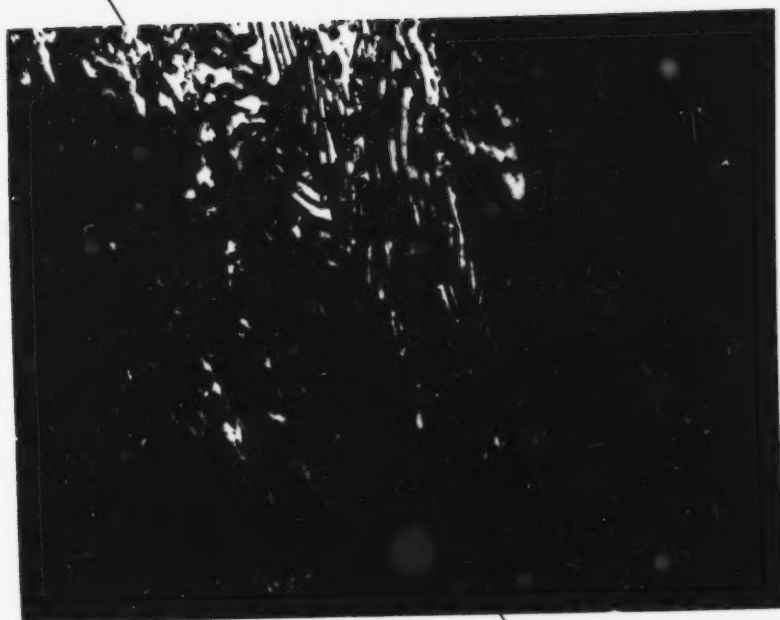


Figure 68a: Sample HQ, 20 um (Neg. 3505)

1.0 μ m



Figure 68b: Diffraction pattern corresponding to figure 68a.
(Neg. 3506)

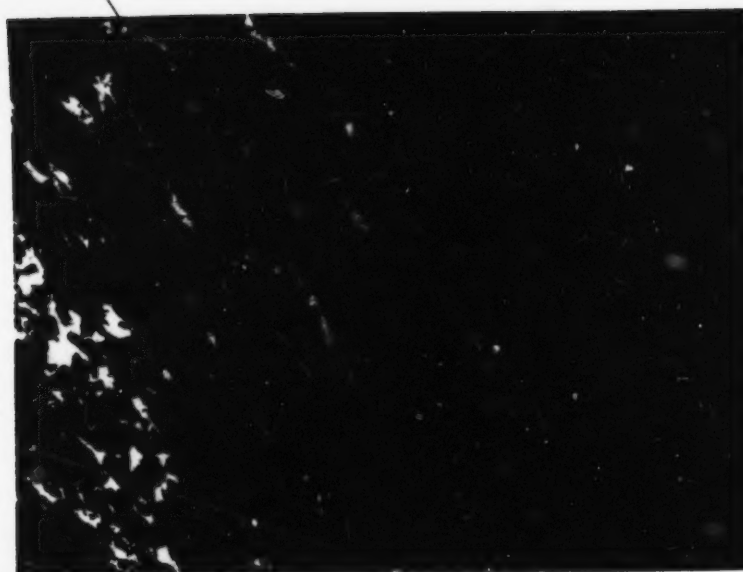


Figure 69a: Sample HQ, 25 um (Neg. 3520)

1.0 μm

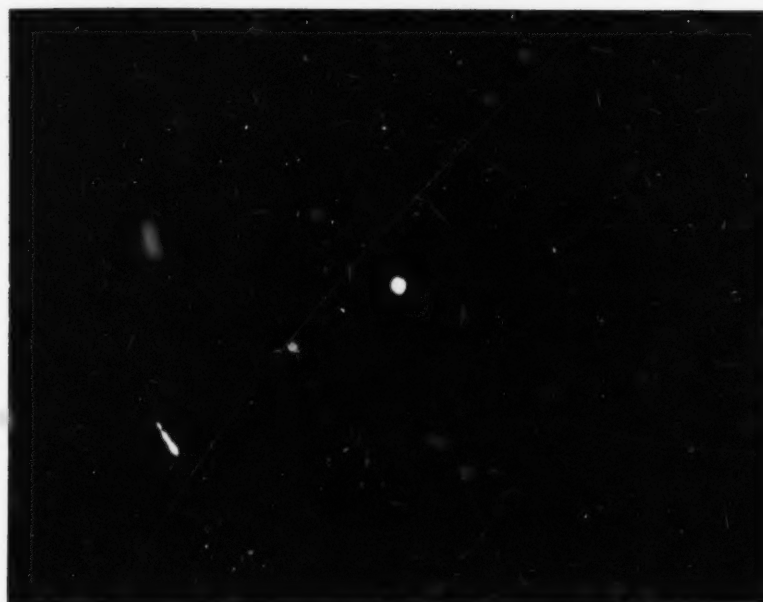


Figure 69b: Diffraction pattern corresponding to figure 69a.
(Neg. 3521)

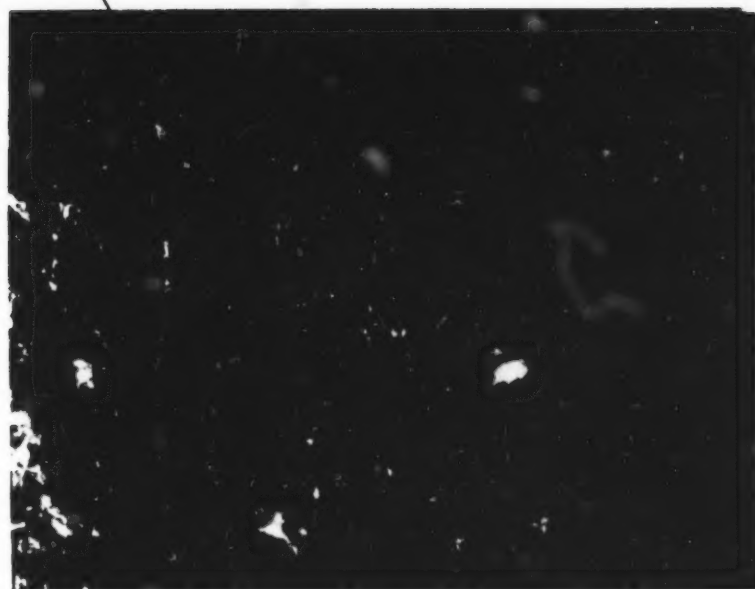
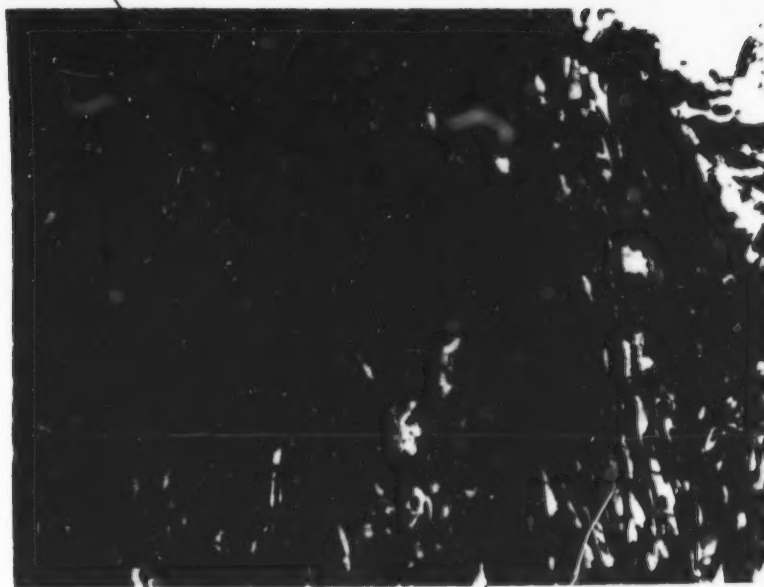


Figure 70a: Sample HGF, 8 um (Neg. 3478)

——— 1.0 μ m



Figure 70b: Diffraction pattern corresponding to figure 70a.
(Neg. 3479)



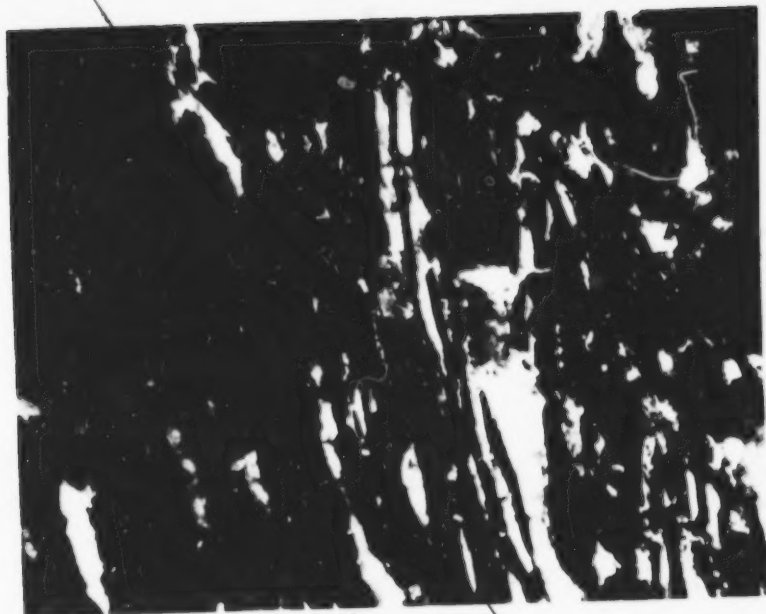
1.0 μ m

Figure 71: Sample HGF, 20 um (Neg. 3480)



1.0 μ m

Figure 72: Sample HGF, 20 um, dark field on 110 (Neg. 3482)



1.0 μ m

Figure 73a: Sample SH, 20 μ m (Neg. 3407)

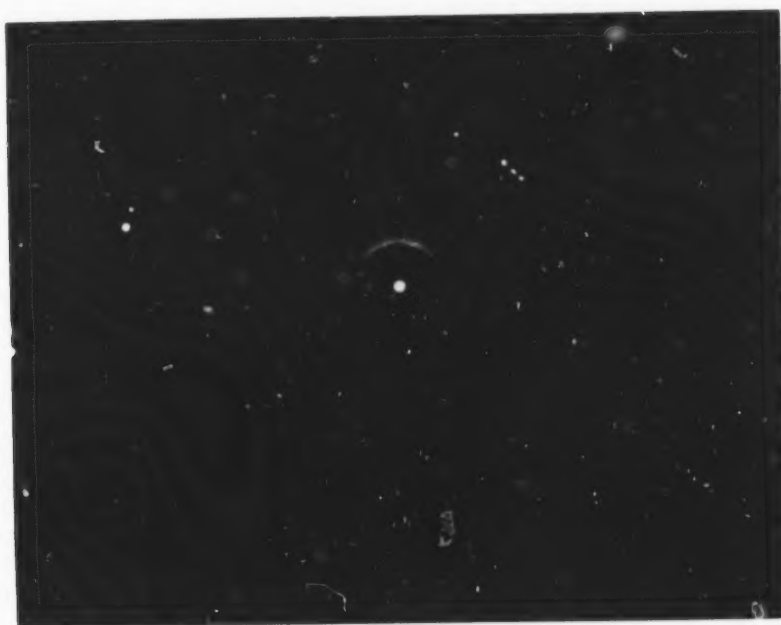


Figure 73b: Diffraction pattern corresponding to figure 73a.
(Neg. 3408)

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Figure 74a: Sample SH, 30 um (Neg. 3485)

1.0 μ m



Figure 74b: Dark field same area as figure 74a, 110 reflection (Neg. 3487)

1.0 μ m

F-68



Figure 75a: Sample SQ, 10 um (Neg. 3449)

1.0 μ m



Figure 75b: Diffraction pattern corresponding to figure 75a.
(Neg. 3450)

F-69



Figure 76: Sample SQ, 15 um (Neg. 3451)

————— 1.0 μ m

F-70



Figure 77a: Sample SGC, 30 um (Neg. 3267)

1.0 μ m

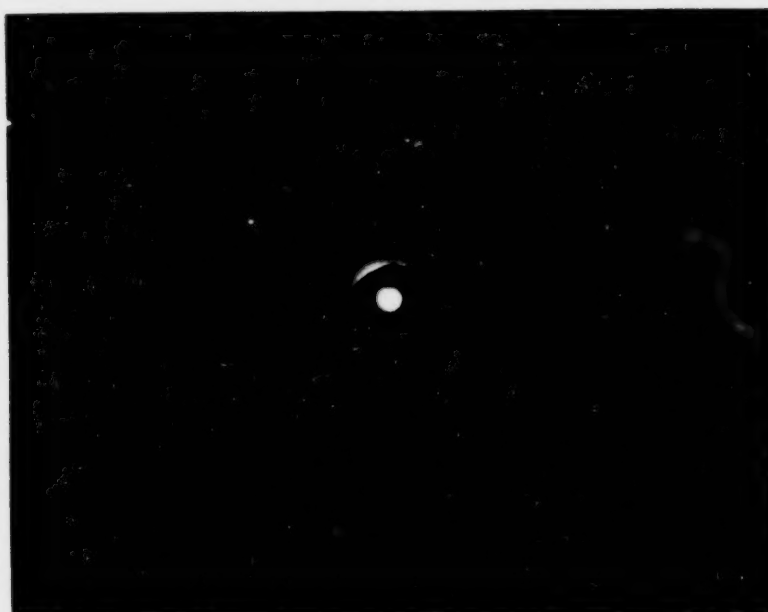


Figure 77b: Diffraction pattern corresponding to figure 77a.
(Neg. 3268)

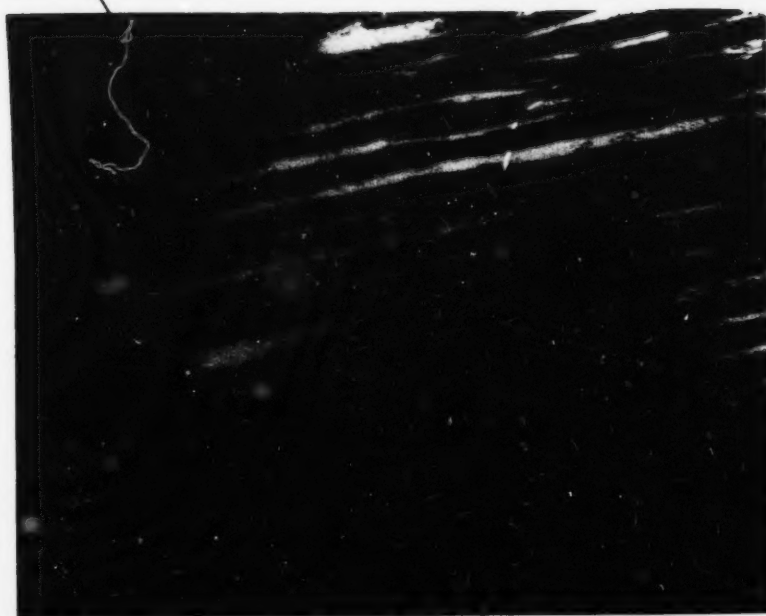


Figure 78a: Sample SGF, 15 um (Neg. 3329)

1.0 μ m

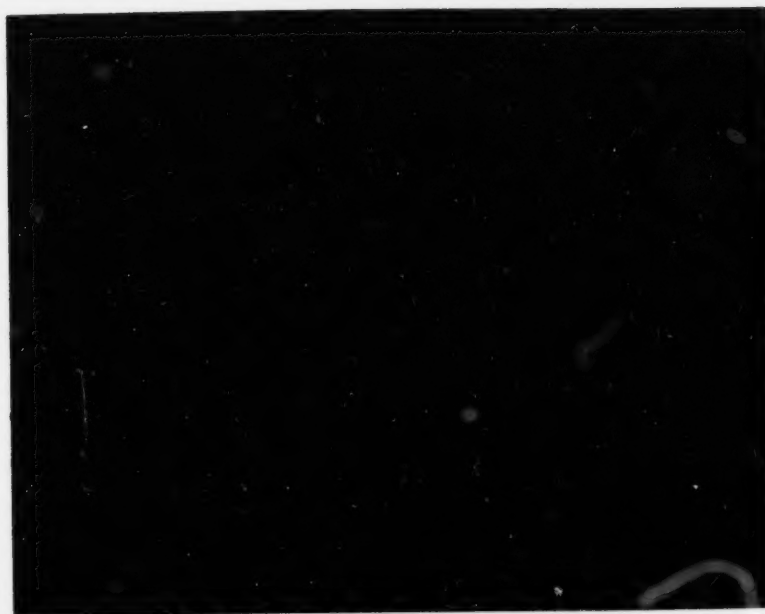


Figure 78b: Diffraction pattern corresponding to figure 78a.
(Neg. 3330)

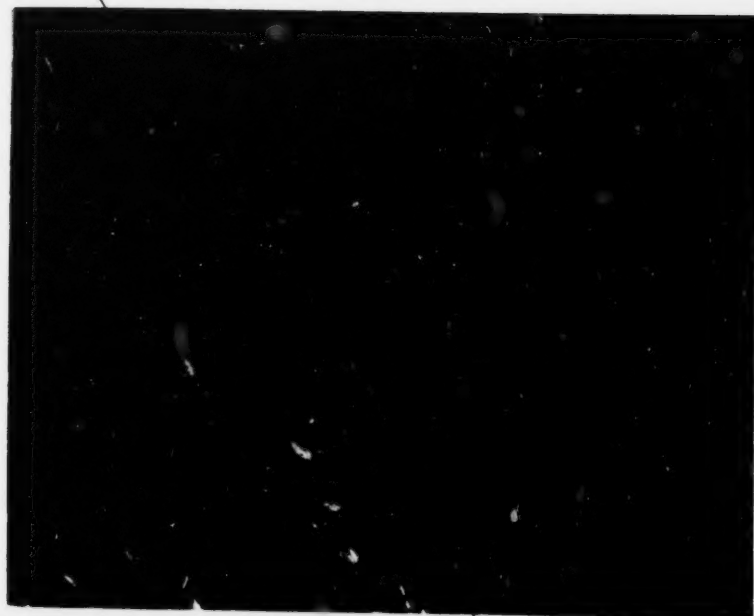


Figure 79a: Sample SGF, 20 um (Neg. 3502)

1.0 μ m



Figure 79b: Diffraction pattern corresponding to figure 79a.
(Neg. 3503)